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Title: Novel Terahertz Metamaterials

Author(s): Taylor, Antoinette

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70 YEARS OF CREATING TOMORROW

Los Alamos NATIONAL LABORATORY

Novel Terahertz Metamaterials

A.J. Taylor

University of Rochester, Institute of Optics Colloquium

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NNSA National Nuclear Security Administration

Center for Integrated Nanotechnologies

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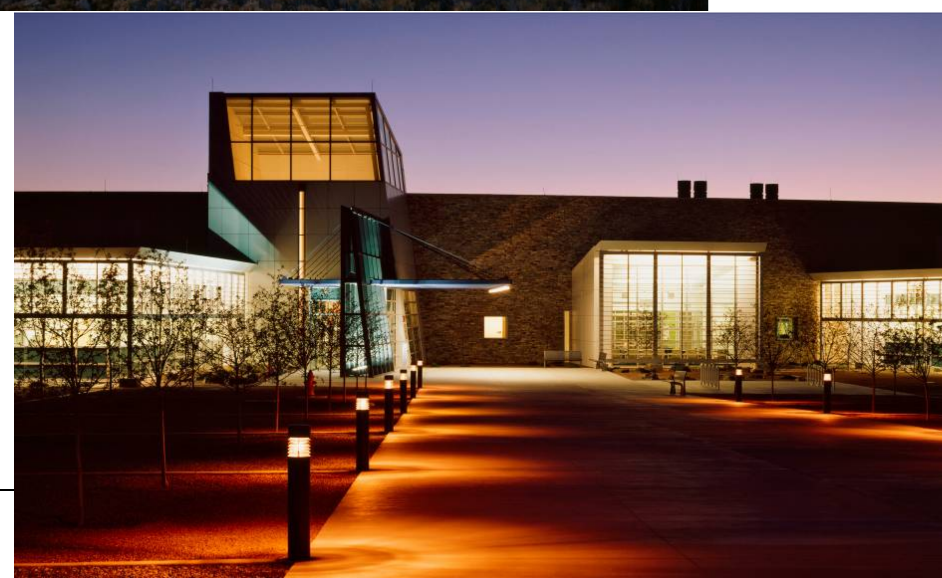
- State-of-the-art facilities
- Leverages LANL and Sandia capabilities
- Develop innovative approaches to nanoscale integration



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Collaborators/Acknowledgements

LANL: H.-T. Chen, A.K. Azad, N.K. Grady, Y. Zeng, D.A.R Dalvit, S. Trugman, Q. Jia. M. Reiten, S. Ramani

Boston University: Rick Averitt

Boston College: Willie Padilla

Oklahoma State University: Weili Zhang, John O'Hara

Rice University: Dan Mittleman

Sandia National Laboratories: Igal Brener

University of Delaware: Josh Zide

University of South Florida: Jiangfeng Zhou

Nantang Technical University: Ranjan Singh, Dibakar Chowdhury

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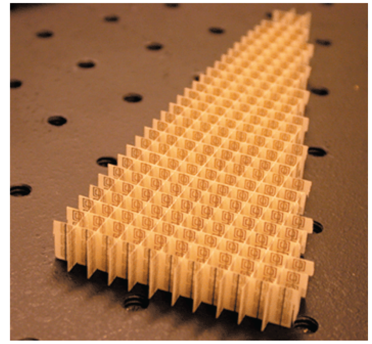
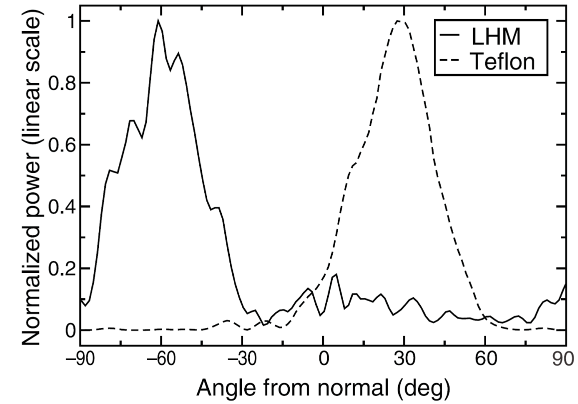
Outline

- **Metamaterials as a solution to the Terahertz (THz) Gap**
- **THz functionalities achieved in few-layered ultrathin planar metamaterials**
    - Antireflection
    - Perfect absorption
    - Linear polarization conversion
    - Anomalous reflection/refraction (generalized Snell's law)
- **Active THz Metamaterials**
    - modulator/switch
    - active frequency tuning
    - spatial modulator
    - thermal and optical tuning using complex oxides
- **Summary**

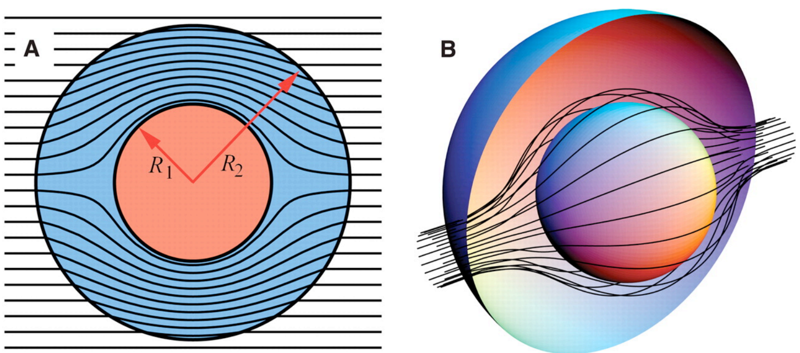
Emergent Phenomena in Metamaterials

- **Metamaterials** are a class of man-made effective media with properties attained from their subwavelength structures rather than the chemical compositions

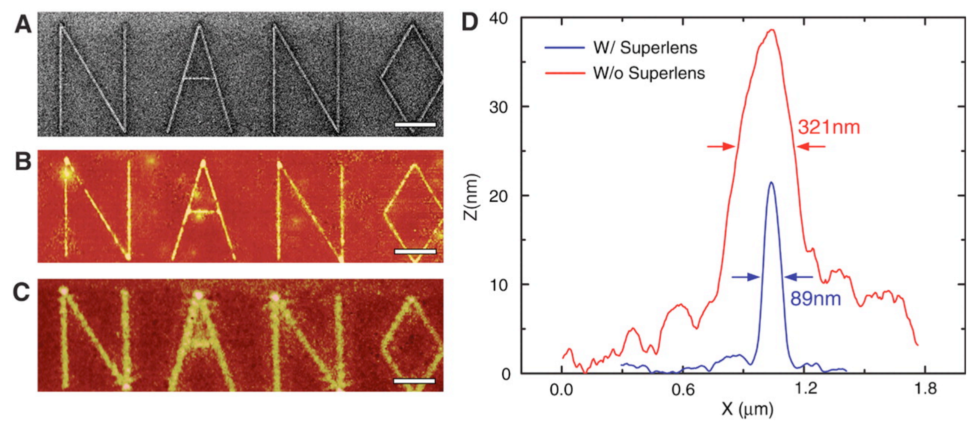




- Negative index of refraction

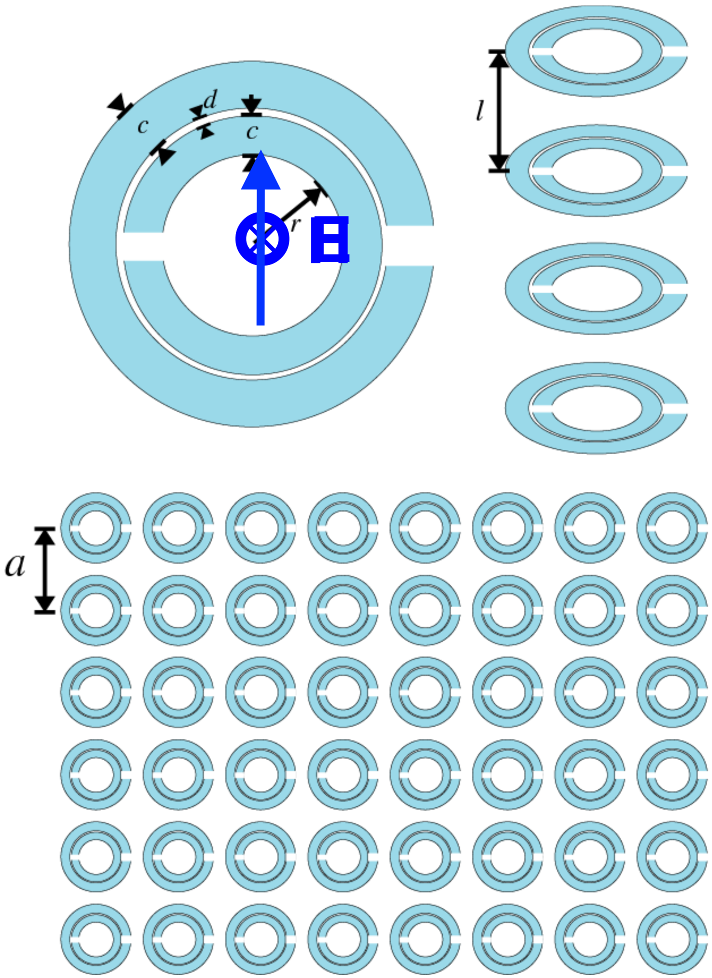


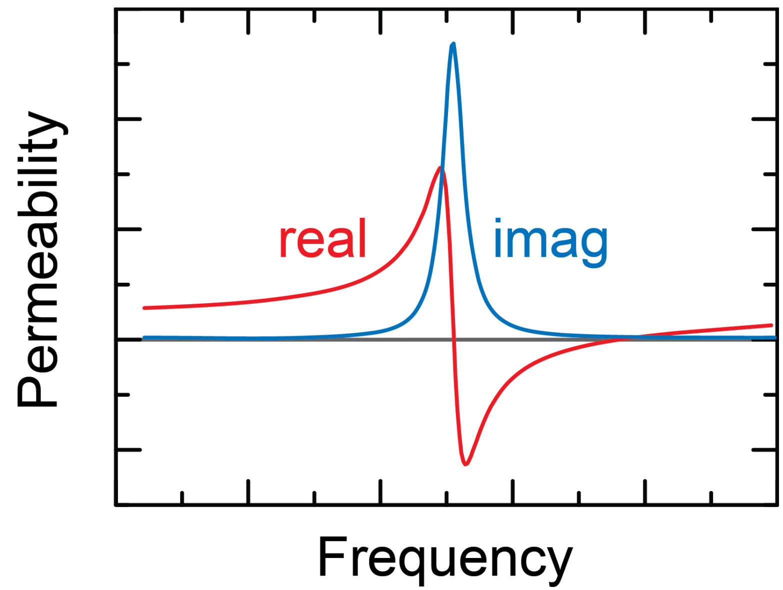
- Cloaking and transformation optics



- Superlens – breaking the diffraction limits

Tunable μ and ε: the Split Ring Resonator (SRR)



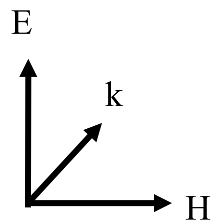


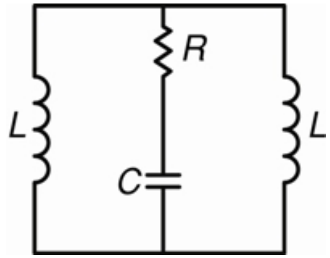
- Magnetic resonance
- Electric resonance

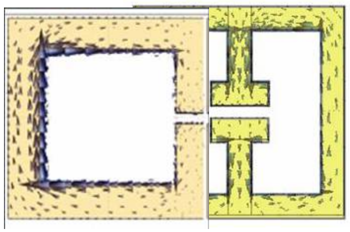
$$\mu_{eff} = 1 - \frac{\frac{\pi r^2}{a^2}}{1 + \frac{2\sigma i}{\omega r \mu_0} - \frac{3}{\pi^2 \mu_0 \omega^2 C r^3}}$$

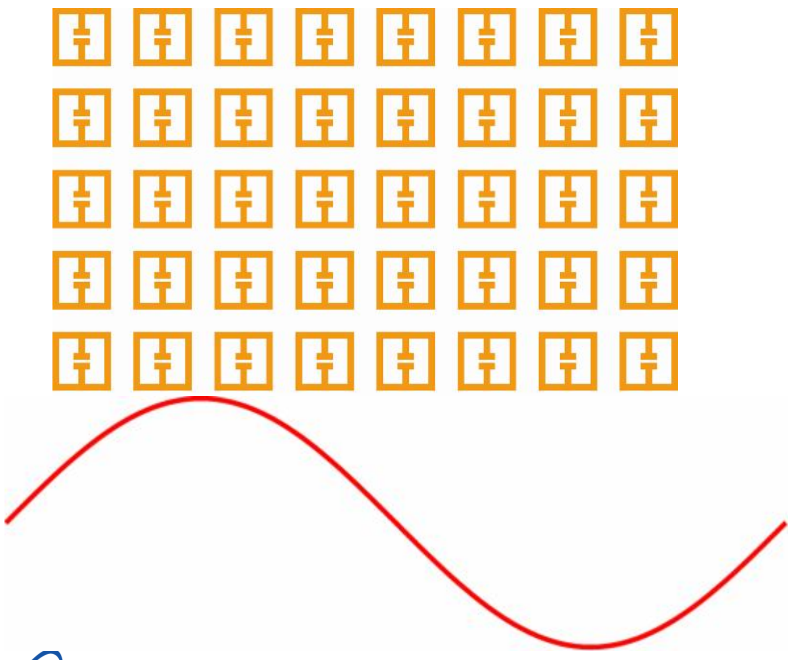
Pendry *et al.*, *IEEE Trans. Microwave Tech.* **47**, 2075 (1999).

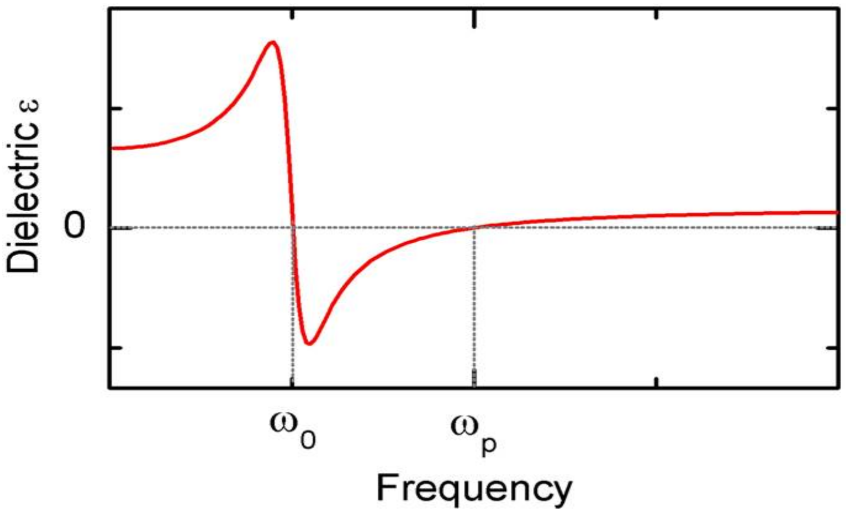
Tunable Electric Metamaterials











$\varepsilon < 0$ when $\omega_0 < \omega < \omega_p$

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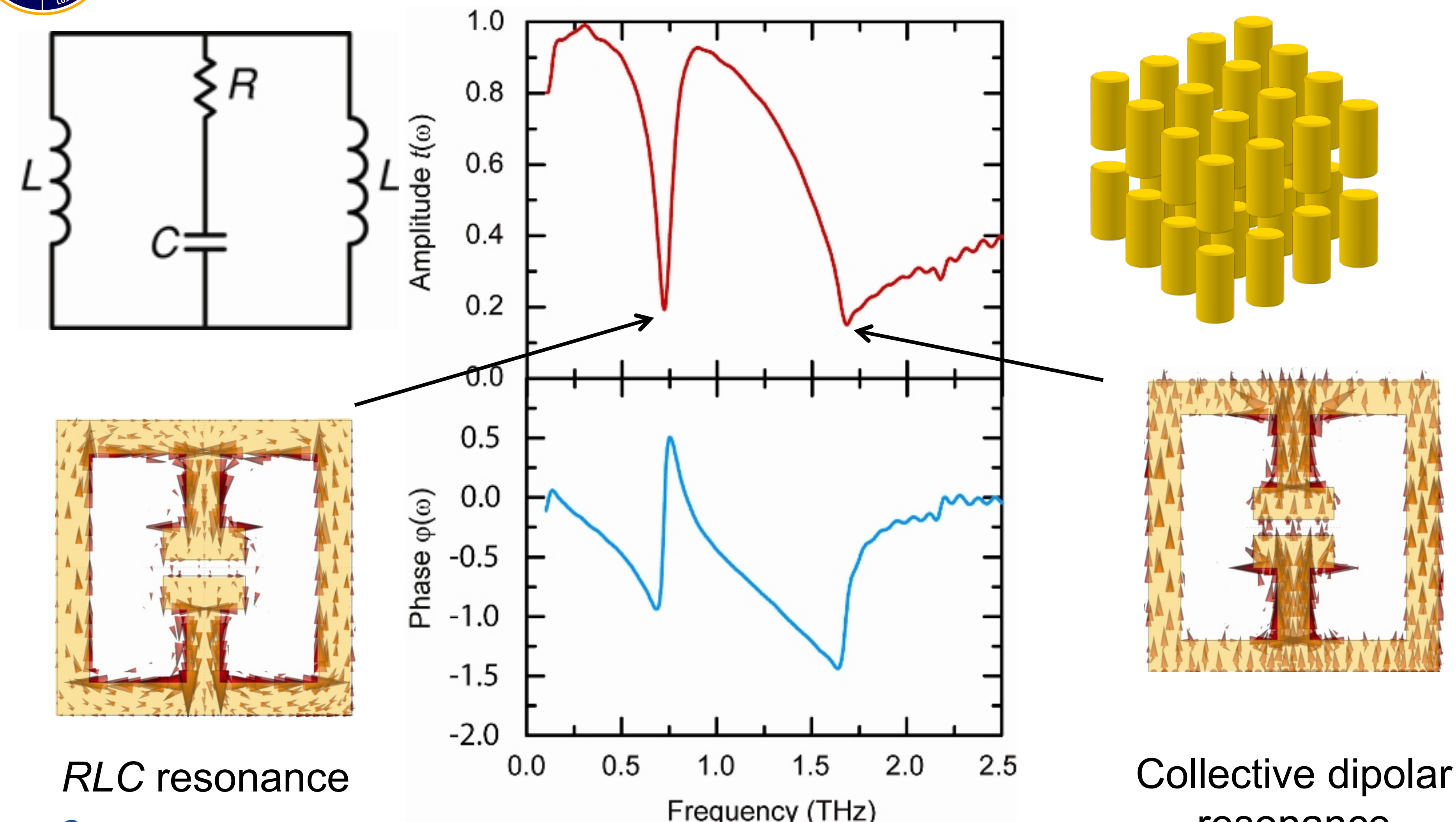
W. J. Padilla et al, Phys. Rev B 75 (2007).

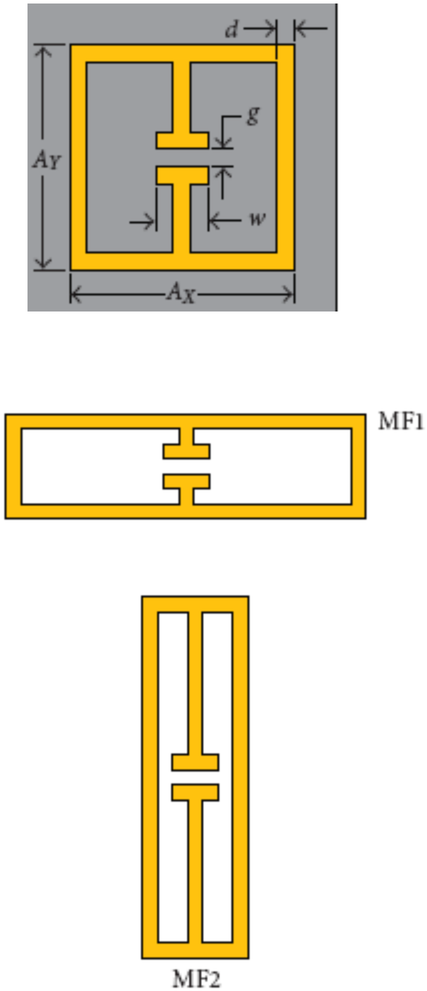
Metamaterial Electric Resonances

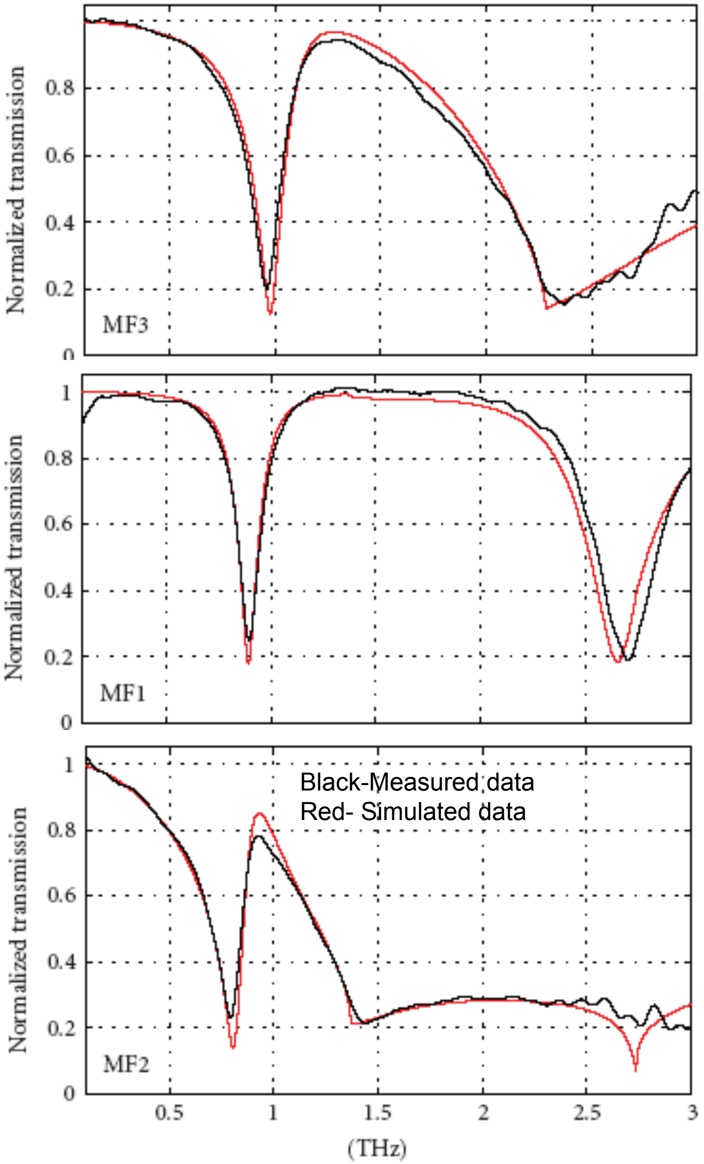


RLC resonance

Collective dipolar resonance

Rectangular eSRR – Engineering Resonances



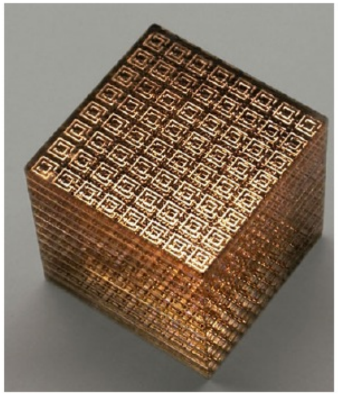


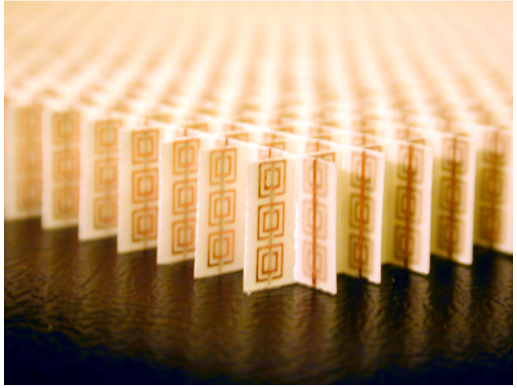
Azad *et al.*, *Appl. Phys. Lett.* **92**, 011119 (2008)

Bulk Metamaterials vs Planar Meta-Surfaces

Bulk metamaterials

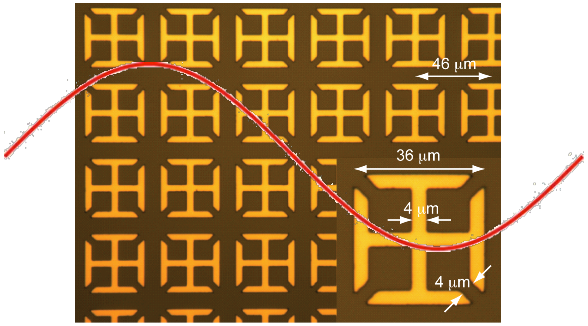
- ❑ Effective material parameters: ε, μ, Z, n
- ❑ Feasible mostly at microwave frequencies
- ❑ Difficult to fabricate in the optical regime

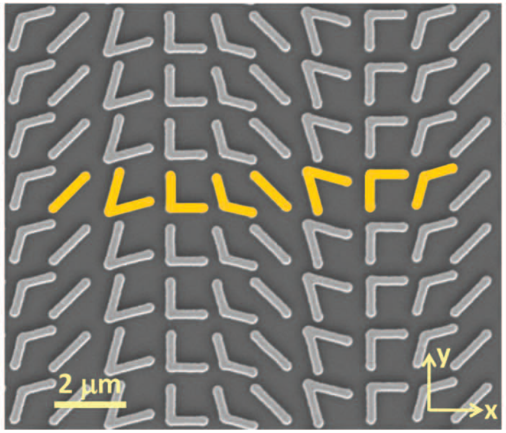




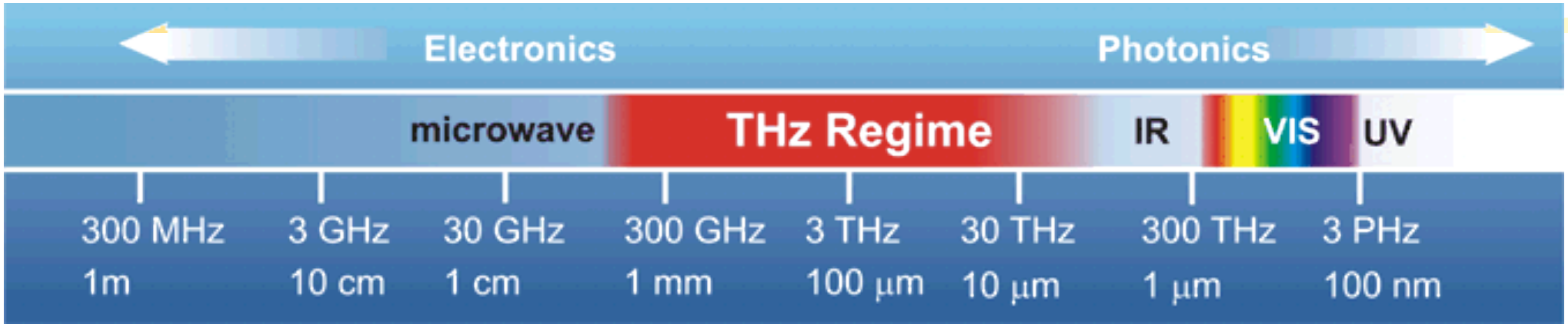
Meta-surfaces

- ❑ Effective surface properties
- ❑ Any relevant frequency
- ❑ Planar structures: ease in fabrication

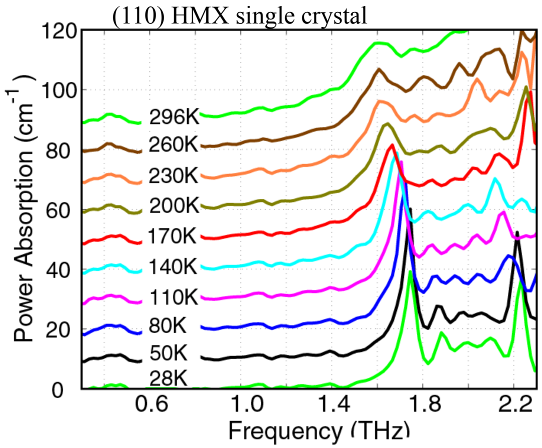




Terahertz Gap

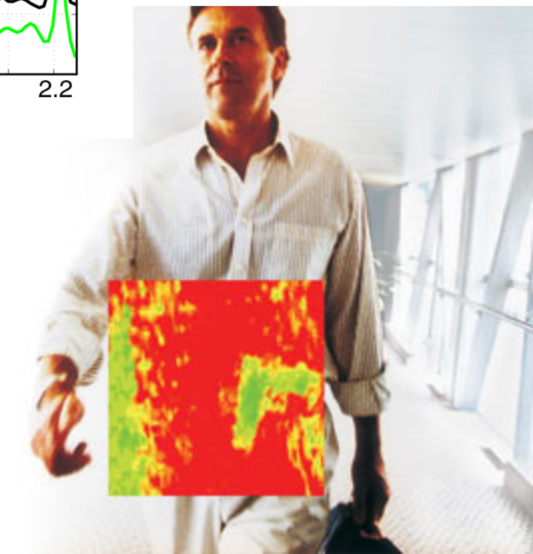


- THz region is located at the interface of electronics and photonics where technologies directly translated from microwave and optical regimes generally fail to operate.
- THz gap is caused by weak materials response at THz frequencies
- Results in a lack of sources, detectors, modulators, filters, polarizers, sensors, etc. in the THz regime.



Spectroscopy

Imaging



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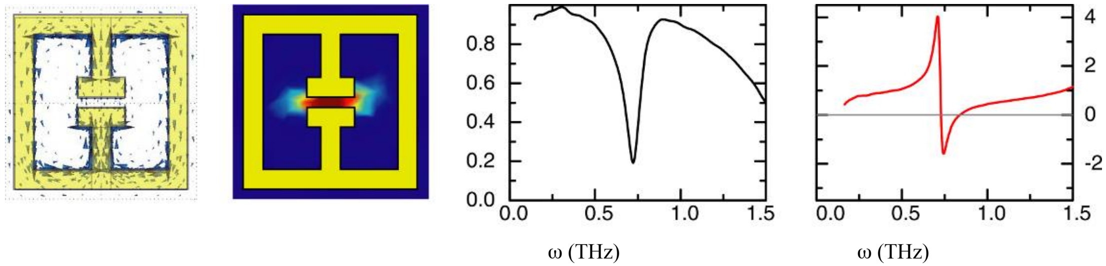
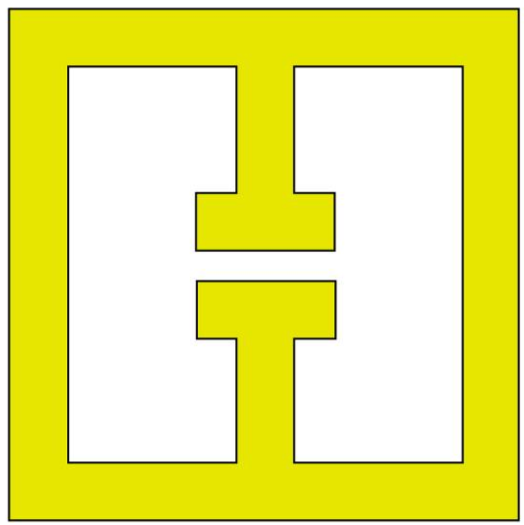
Metamaterials: A solution to the THz Gap





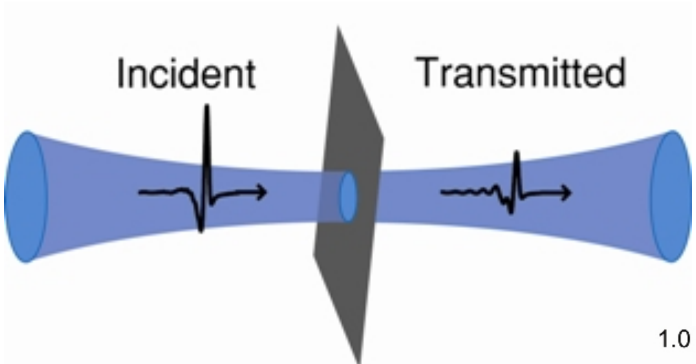
<u>Typical parameters:</u>
Unit cell: 50 μm
Outer dimension: 36 μm
Line width: 4 μm
Split gap: 2 μm

Resonance enhances THz interactions

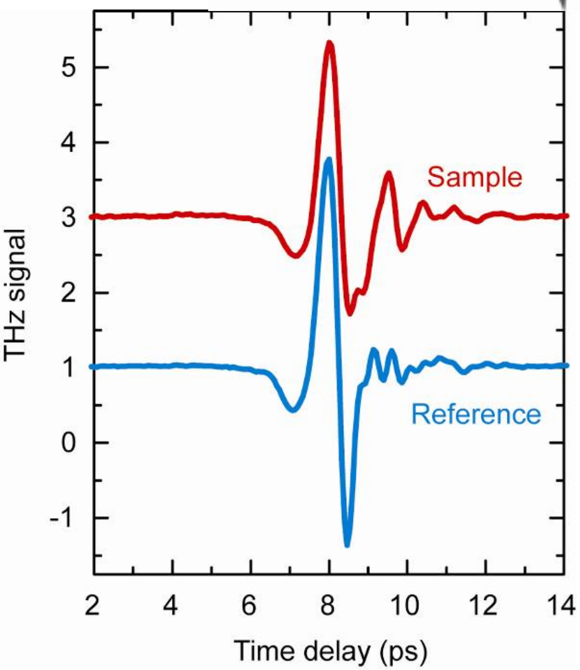
- Modulators (AM, FM, PM)
- Filters
- Sensors

First THz MM: T. J. Yen, W. J. Padilla, et al., Science 393, 1494 (2004).

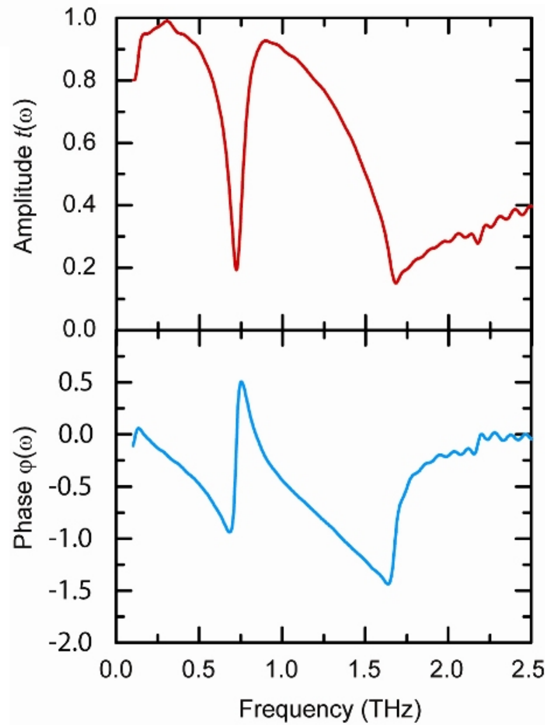
Terahertz Time Domain Spectroscopy (THz-TDS)

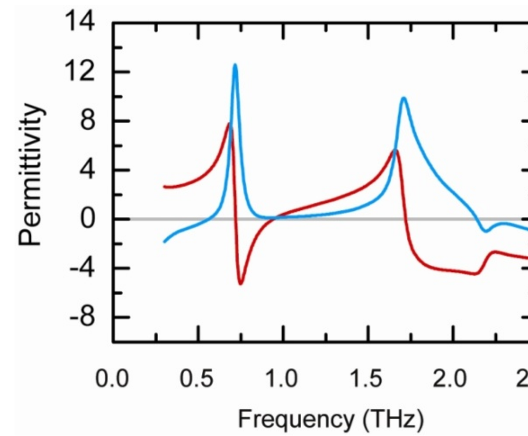


$$\tilde{t}(\omega) = \frac{E_{\mathrm{Sam}}(\omega)}{E_{\mathrm{Ref}}(\omega)}$$



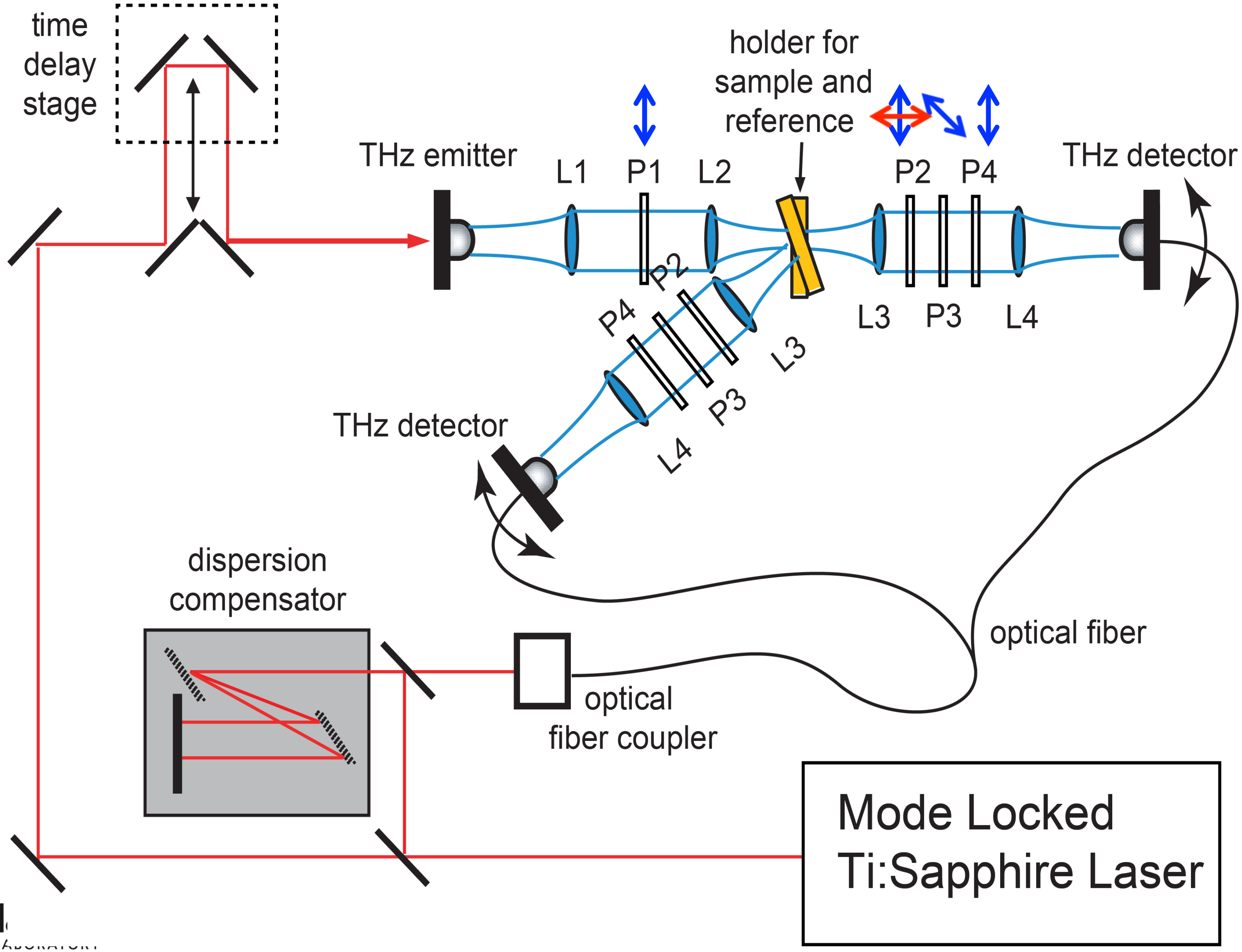
FFT



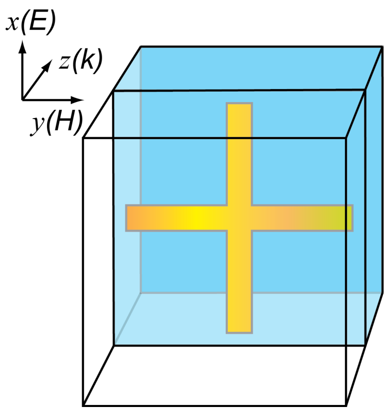


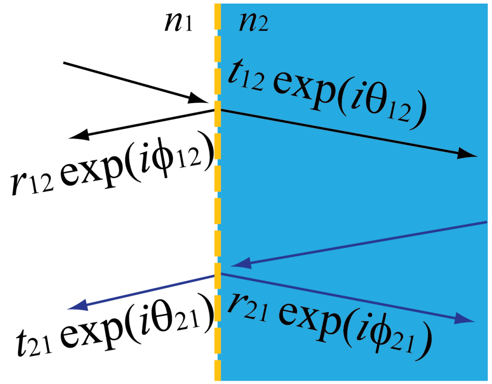
Full extraction of complex optical properties from amplitude $t(\omega)$ and phase $\varphi(\omega)$

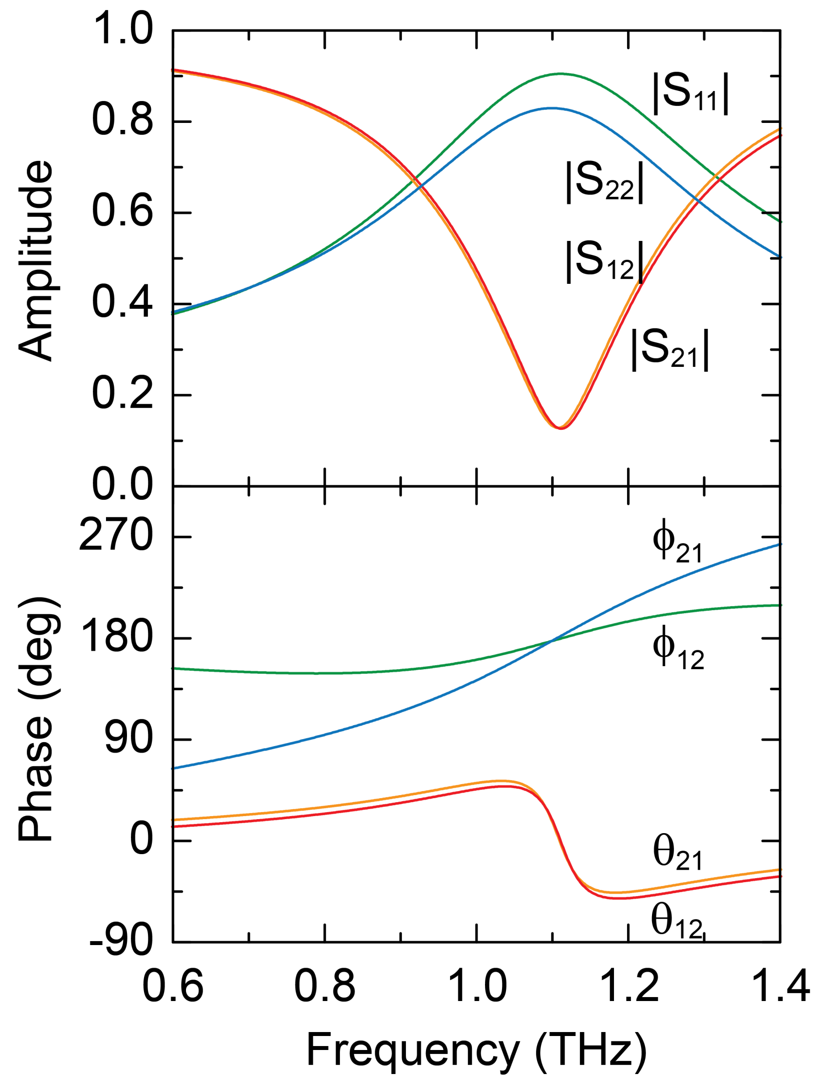
THz spectroscopy in reflection: angular dependence



Tailored Transmission and Reflection







- The resonator array modifies the complex reflection and transmission coefficients at the interface

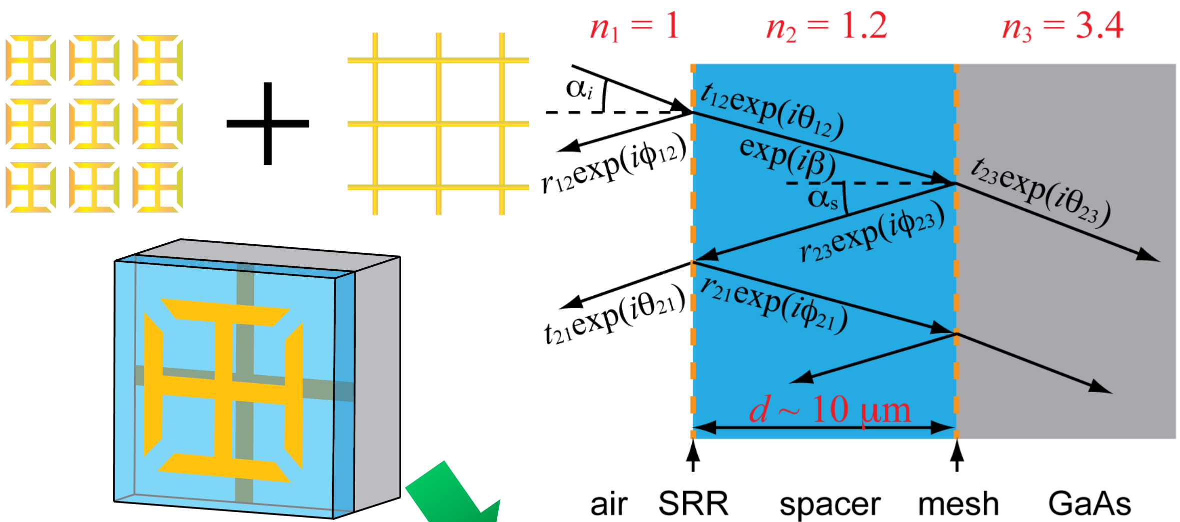
$$r_{12} = |S_{11}| \qquad t_{12} = \sqrt{\frac{n_1}{n_2}}\,|S_{21}|$$

$$r_{21} = |S_{22}| \qquad t_{21} = \sqrt{\frac{n_2}{n_1}}\,|S_{21}|$$

$$\phi_{12} = \arctan(S_{11}) \qquad \theta_{12} = \arctan(S_{21})$$

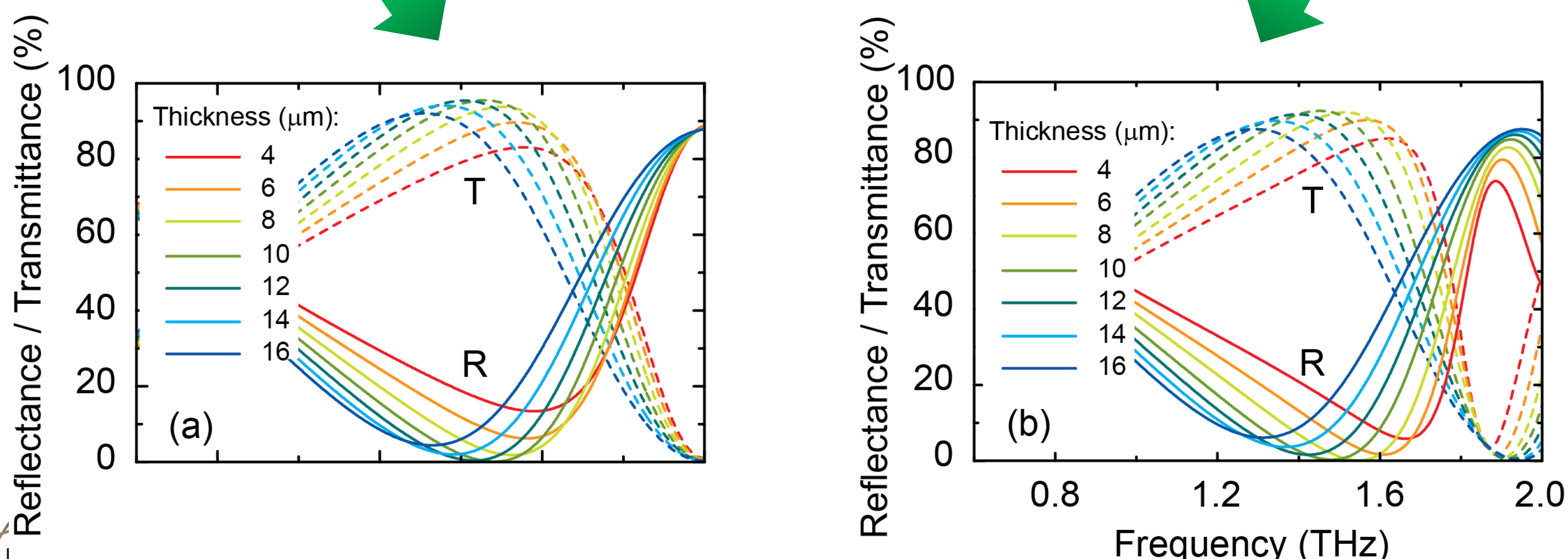
$$\phi_{21} = \arctan(S_{22}) \qquad \theta_{12} = \arctan(S_{12})$$

Ultrathin Metamaterial Anti-Reflection Coating



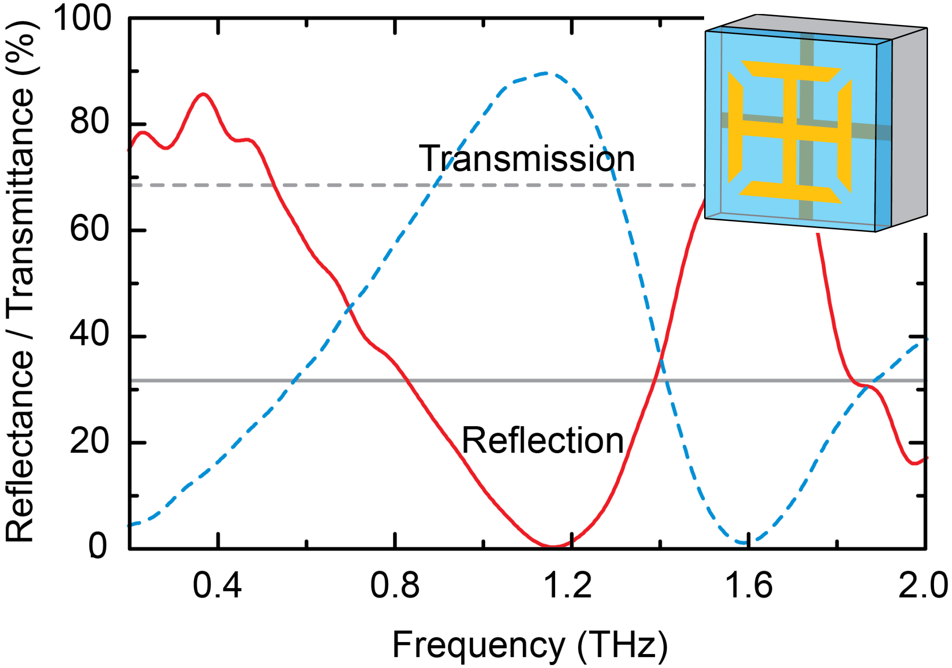
$$\tilde{r} = \tilde{r}_{12} + \frac{\tilde{t}_{12}\tilde{t}_{21}\tilde{r}_{23}e^{i2\tilde{\beta}}}{1 - \tilde{r}_{21}\tilde{r}_{23}e^{i2\tilde{\beta}}}$$

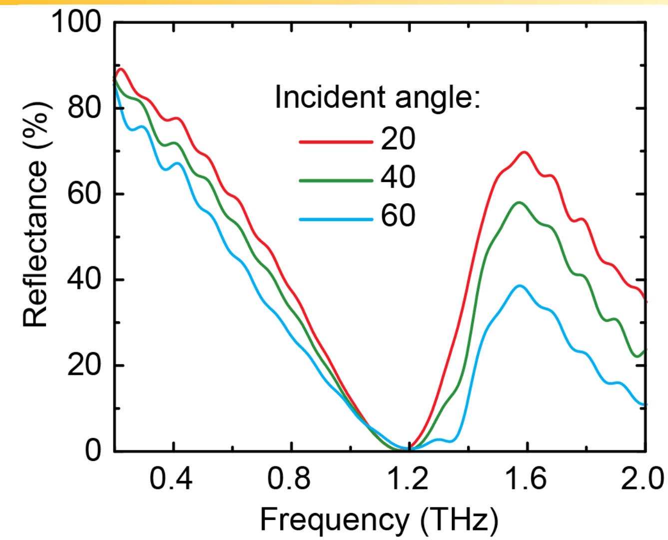
$$\tilde{t} = \frac{\tilde{t}_{12}\tilde{t}_{23}e^{i\tilde{\beta}}}{1 - \tilde{r}_{21}\tilde{r}_{23}e^{i2\tilde{\beta}}}$$

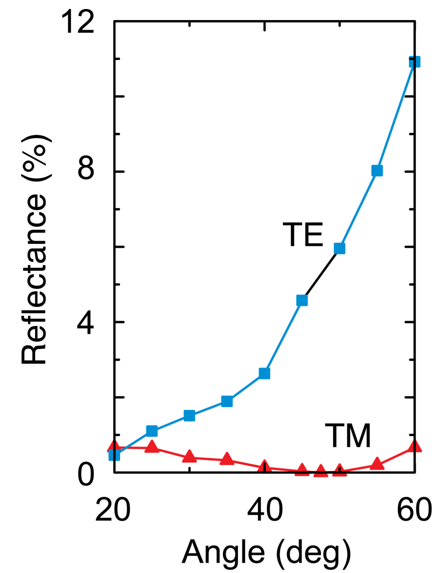


Chen *et al.*, *Phys. Rev. Lett.* **105**, 073901 (2010).

Ultrathin Metamaterial ARC: Experiments



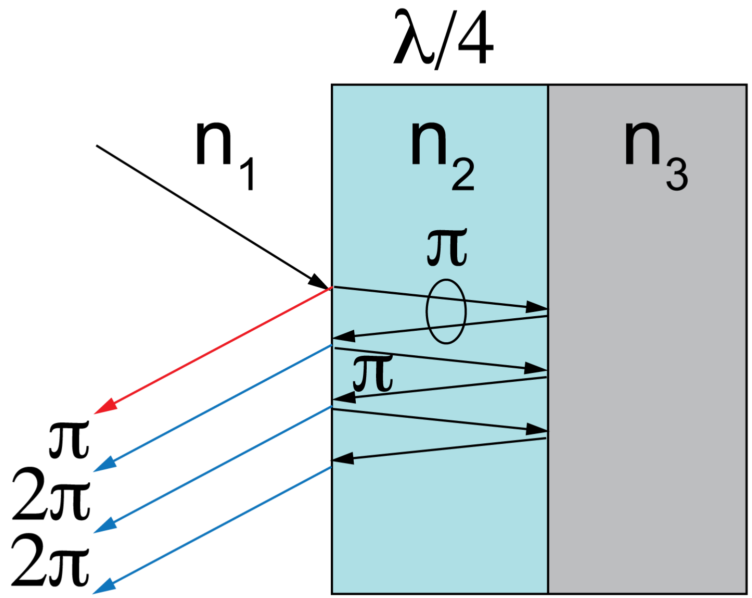


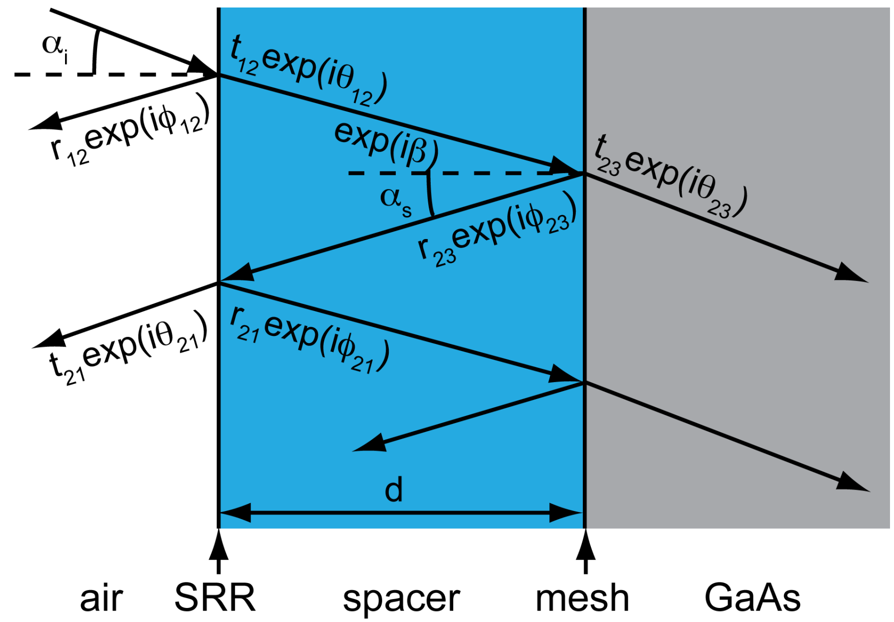


- ❑ Reflectance: 32% → ~0
- ❑ Transmittance: 68% → 90%
- ❑ Transmittance does not reach 100% due to losses
- ❑ Operate over a wide incident angle range
- ❑ Brewster angle behavior for TM polarization

Chen *et al.*, *Phys. Rev. Lett.* **105**, 073901 (2010).

Comparison to Quarter-Wave Antireflection



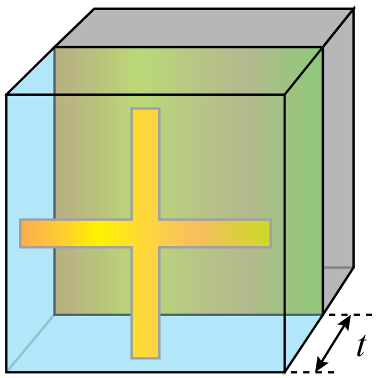


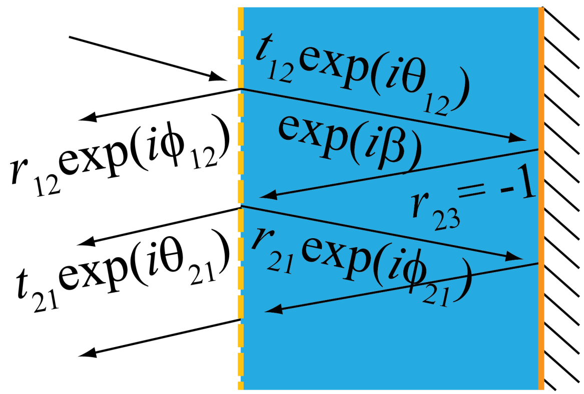
- $n_2 = (n_1 n_3)^{1/2} \backslash\ r_{12} = r_{21} = r_{23}$
- Phase difference π between direct reflection and second reflection
- Phase difference 2π in the following reflections

- At antireflection frequency $r_{12} = r_{21} = r_{23}$
- $(\theta_{12} + \phi_{23} + \theta_{21} + 2\beta) - \phi_{12} = \pi$ between direct reflection and second reflection
- $\phi_{21} + \phi_{23} + 2\beta = 0\ (2\pi)$ in the following reflections

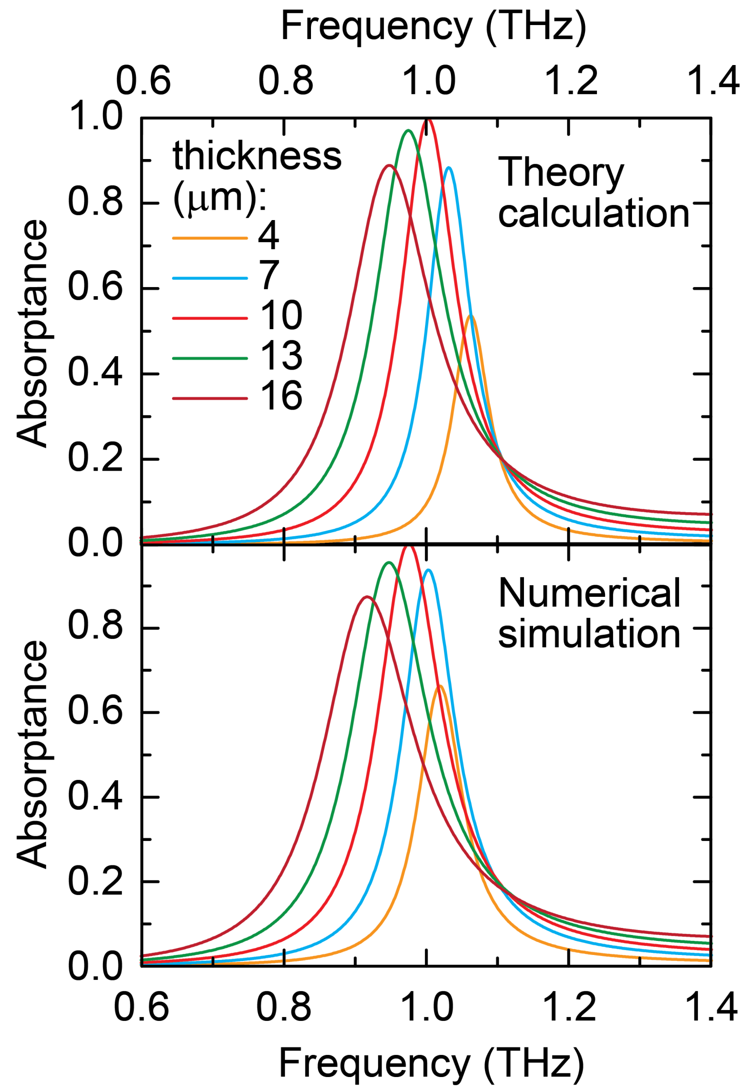
Chen *et al.*, *Phys. Rev. Lett.* **105**, 073901 (2010).

Metamaterial Perfect Absorbers: Trapped Light





$$\tilde{r} = \tilde{r}_{12} + \frac{\tilde{t}_{12}\tilde{t}_{21}\tilde{r}_{23}e^{i2\tilde{\beta}}}{1 - \tilde{r}_{21}\tilde{r}_{23}e^{i2\tilde{\beta}}}$$

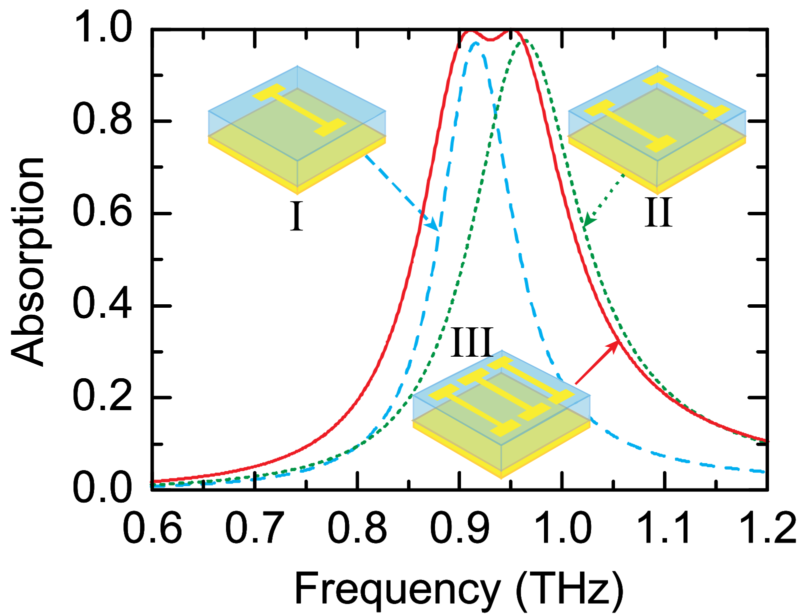


- ❑ Zero transmission due to the metal ground plane
- ❑ Minimizing reflection due to destructive interference of multi-reflection

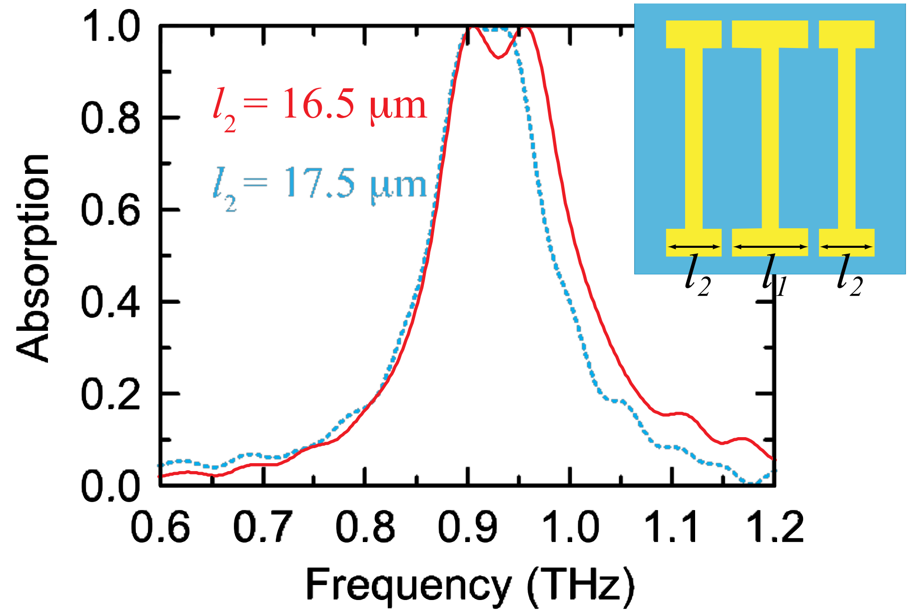
Chen, *Opt. Express* **20,** 7165 (2012).

Bandwidth Broadening for Metamaterial Absorbers

Simulations



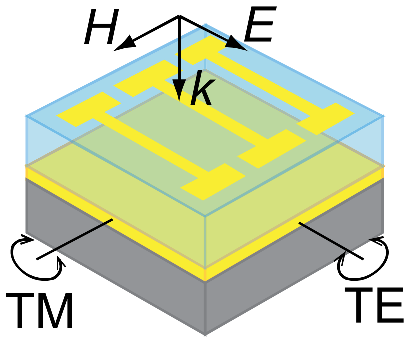
Experiments

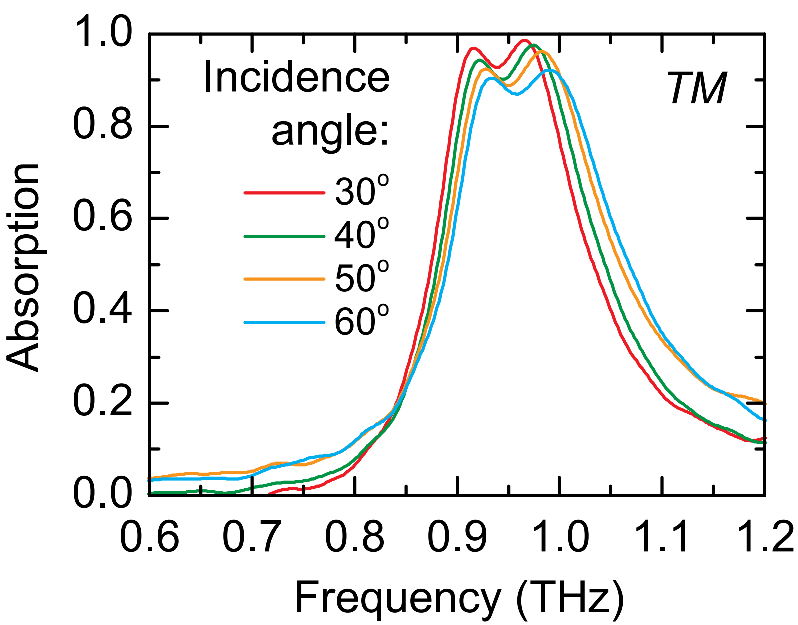


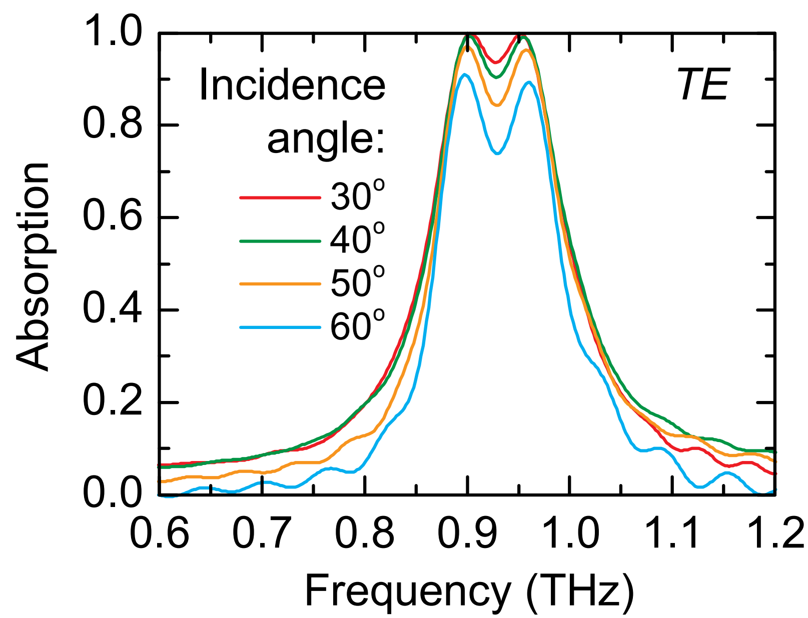
- Broadening the absorption bandwidth by multiplexing

Huang *et al.*, *Opt. Lett.* **37,** 154 (2012).

High Absorption over a Wide Incident Angle Range







Huang *et al.*, *Opt. Lett.* **37,** 154 (2012).

Boundary Surface Currents

- When EM wave first incident to the resonator array interface, the boundary conditions for magnetic field give the surface current:

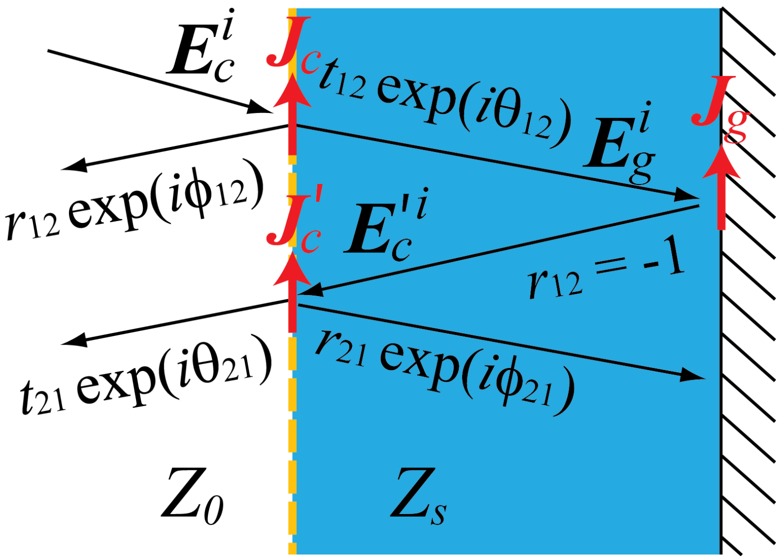
$$J_c = \left[\left(1-\tilde{r}_{12}\right)/Z_0 - \tilde{t}_{12}/Z_s\right] E_c^i$$

- Then it reaches to ground plane and is reflected, the boundary conditions for magnetic field require:

$$J_g = 2E_g^i/Z_s = 2\tilde{t}_{12}e^{i\tilde{\beta}}E_c^i/Z_s$$

- It reaches to resonator interface again:

$$J_c' = \left[\left(1-\tilde{r}_{21}\right)/Z_s - \tilde{t}_{21}/Z_0\right] E_c'^i$$
$$= -\left[\left(1-\tilde{r}_{21}\right)/Z_s - \tilde{t}_{21}/Z_0\right] \tilde{t}_{12}e^{i2\tilde{\beta}}E_c^i$$



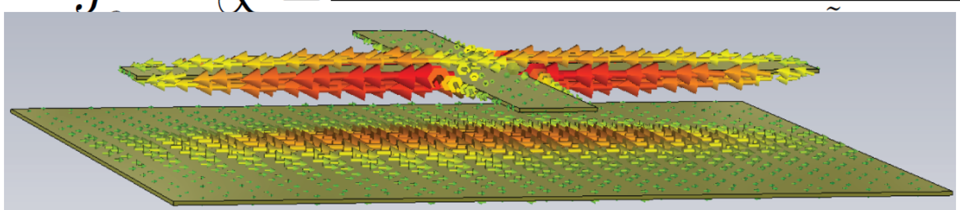
Chen, *Opt. Express* **20,** 7165 (2012).

Anti-Parallel Surface Currents by Electrical Excitations

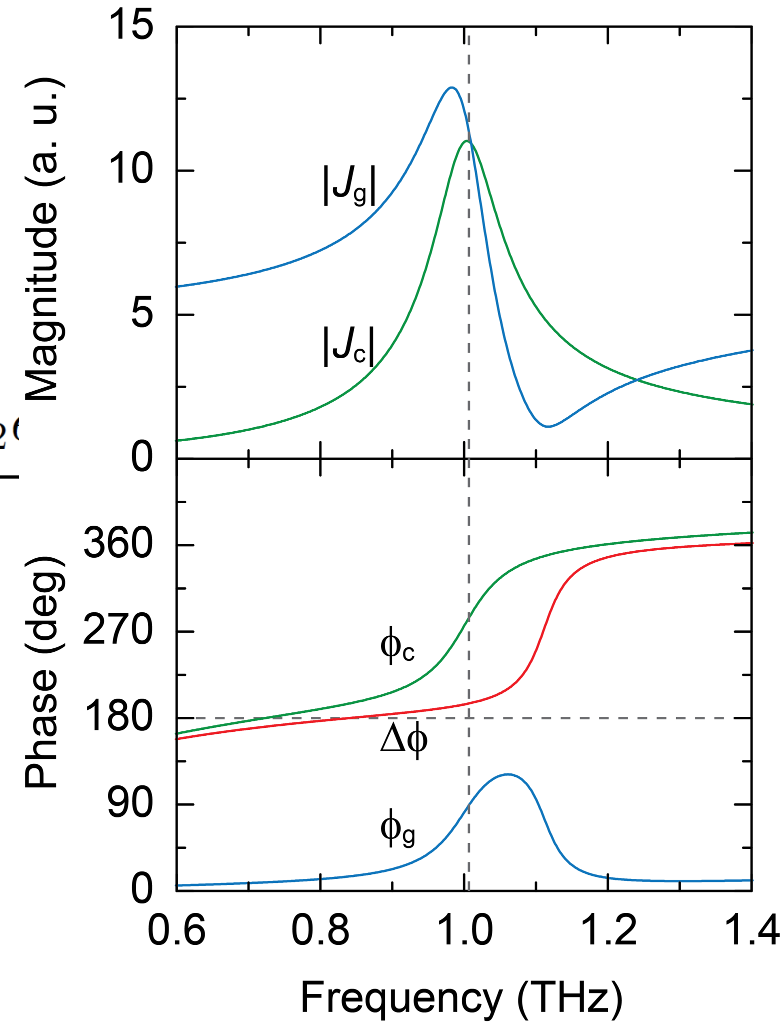
- The total surface currents are the superpositions of each excitation:

$$J_g^{total} \propto \frac{2\tilde{t}_{12}e^{i\tilde{\beta}}}{1+\tilde{r}_{21}e^{i2\tilde{\beta}}}/Z_s$$

$$J_c^{total} \propto -\frac{\left[\left(1-\tilde{r}_{21}\right)/Z_s-\tilde{t}_{21}/Z_0\right]\tilde{t}_{12}e^{i2\tilde{\beta}}}{1+\tilde{r}_{21}e^{i2\tilde{\beta}}}+\left[\left(1-\tilde{r}_{12}\right)/Z_0-\tilde{t}_{12}/Z_s\right]$$

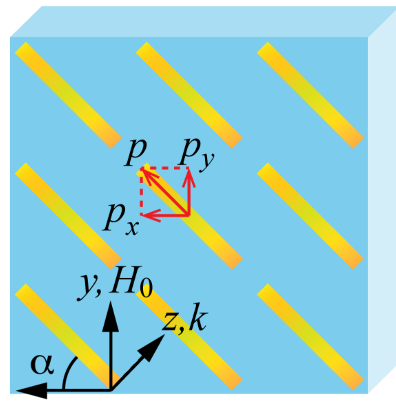


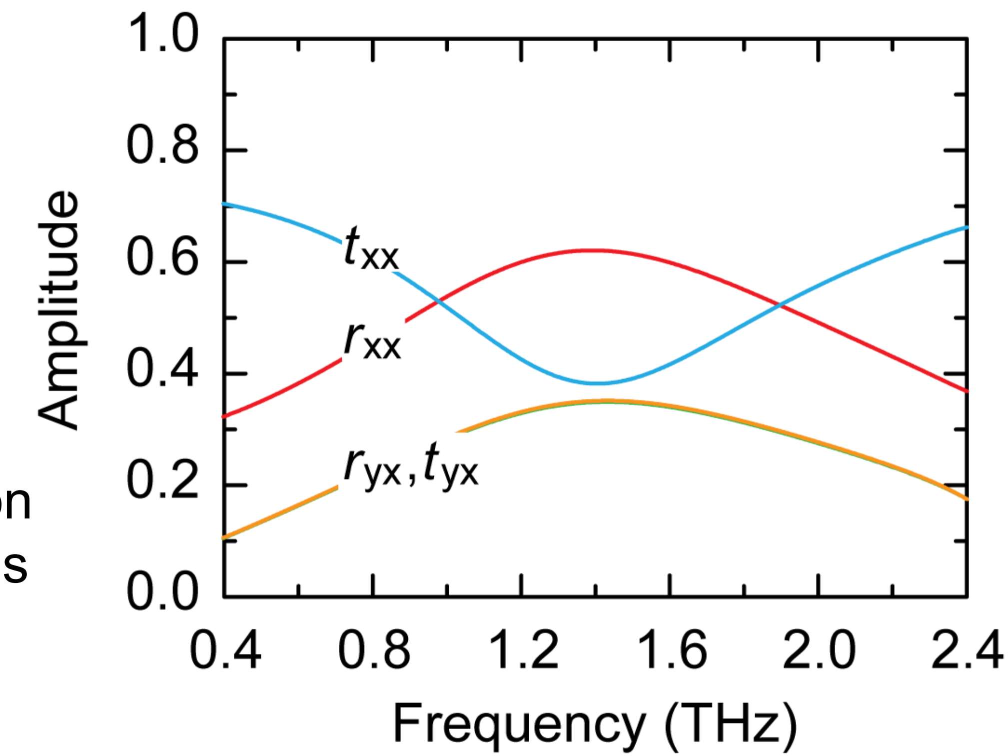
- Anti-parallel surface currents are due to interference and superposition of electrical excitations



Chen, *Opt. Express* **20,** 7165 (2012).

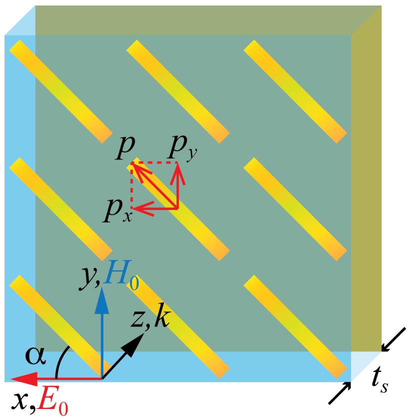
Polarization Conversion in Anisotropic MMs



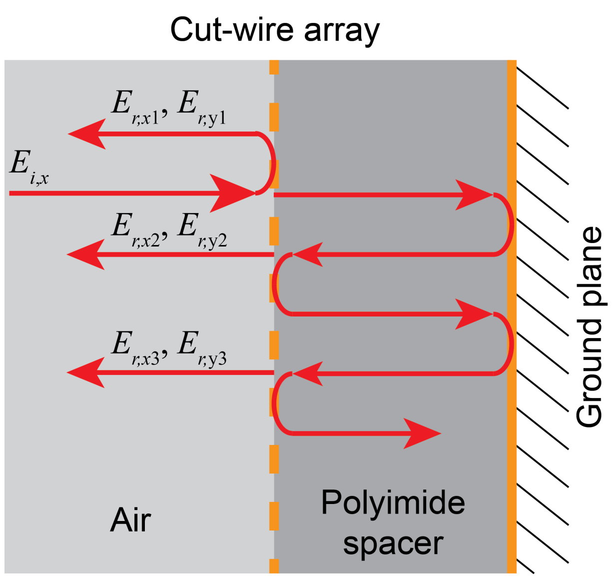


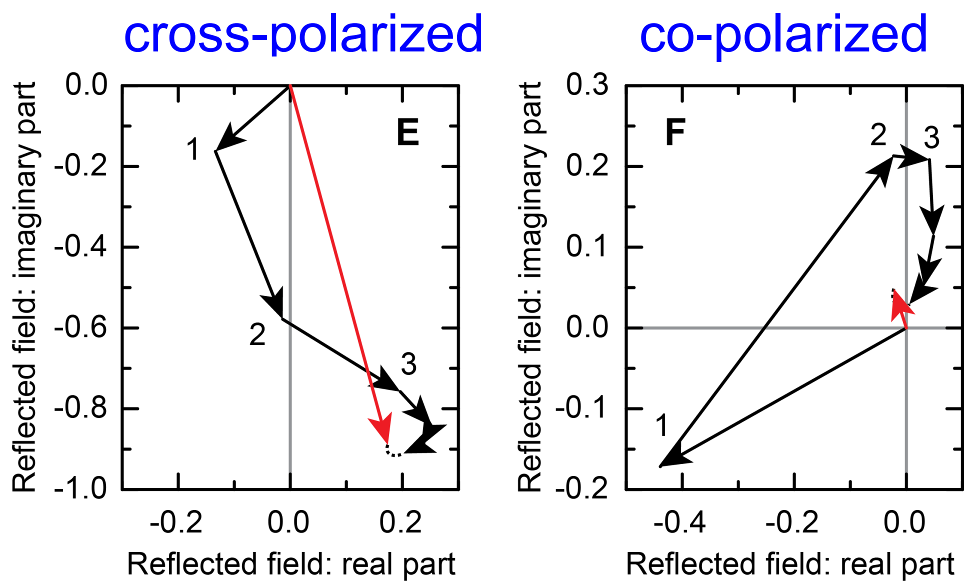
- Incident field $\boldsymbol{E}_0$ along *x*-direction (α=45°): the excited dipole ***p*** has *x*- and *y*-components
- p_x: co-polarized reflection and transmission
- p_y: cross-polarized reflection and transmission
- Single-layered metamaterial: polarization conversion is low
- Output waves are elliptically polarized

Metamaterial Polarization Converter: Reflection



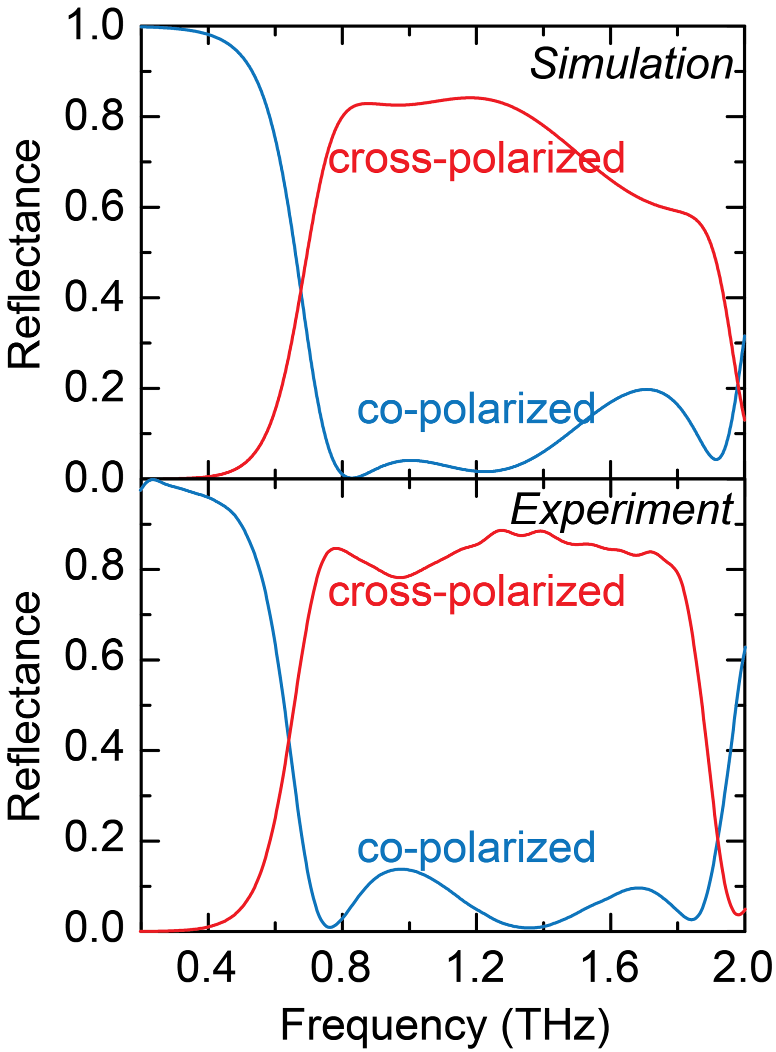
- Backed with a metal ground plane with appropriate thick dielectric spacer
- Multiple reflections contain both x and y components
- The co-polarized multiple reflections interfere destructively, leading to minimal co-polarized reflection
- The cross-polarized multiple reflections interfere constructively, leading to high cross-polarized reflection





Grady et al., *Science* **340**, 1304 (2013).

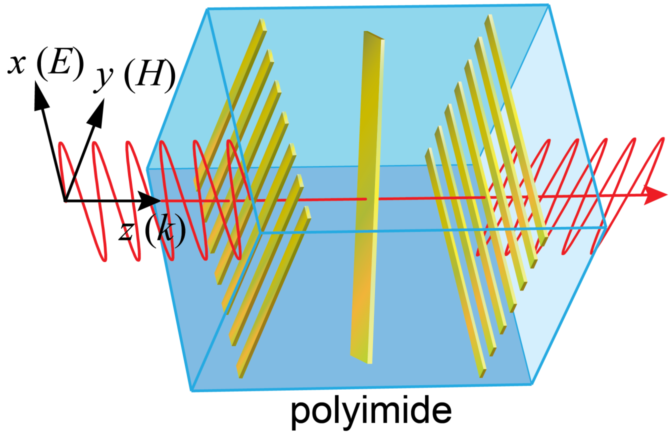
Metamaterial Polarization Converter: Reflection

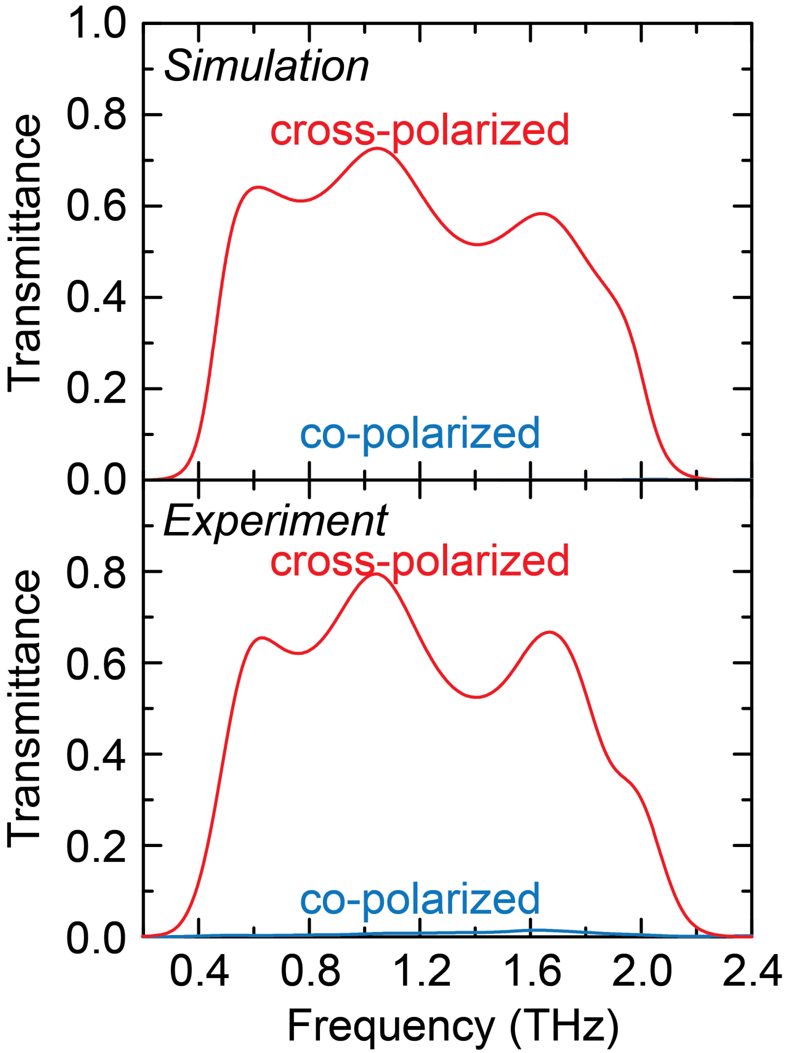


- ❑ Demonstrated in both simulations and experiments
- ❑ Device thickness 33 μm
- ❑ Co-polarized reflection is minimal
- ❑ Cross-polarized reflectance is more than 80%
- ❑ Broadband: destructive interference at multiple frequencies

Grady et al., *Science* **340**, 1304 (2013).

Polarization Converter: Transmission

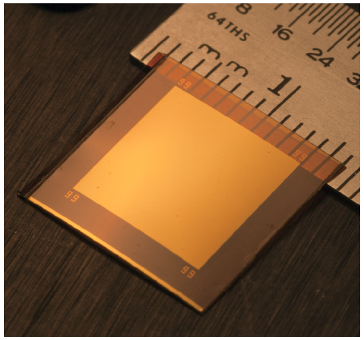


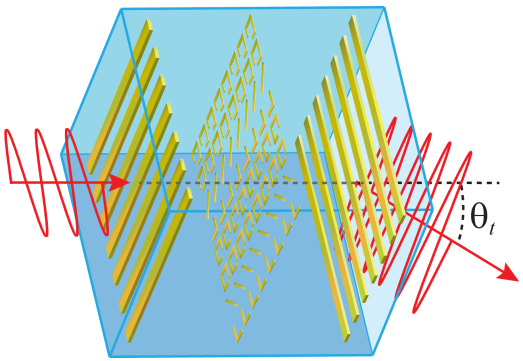


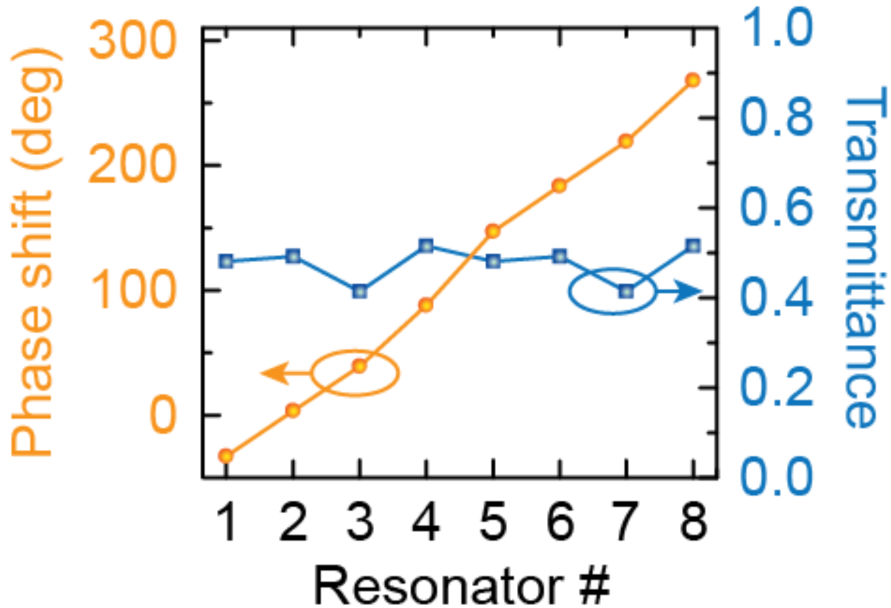
- The gratings are equivalent to ground plane for electric field polarized along the grating lines.
- The back grating prevents co-polarized light from transmitting through
- The front grating prevents the converted cross-polarized light from reflecting back

Grady et al., *Science* **340**, 1304 (2013).

Anomalous Refraction: Generalized Snell's Law





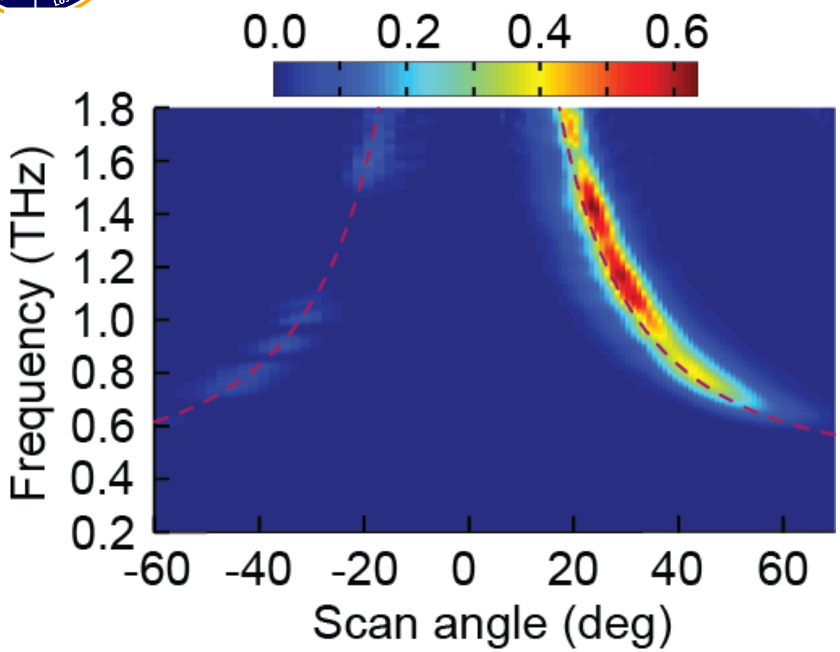


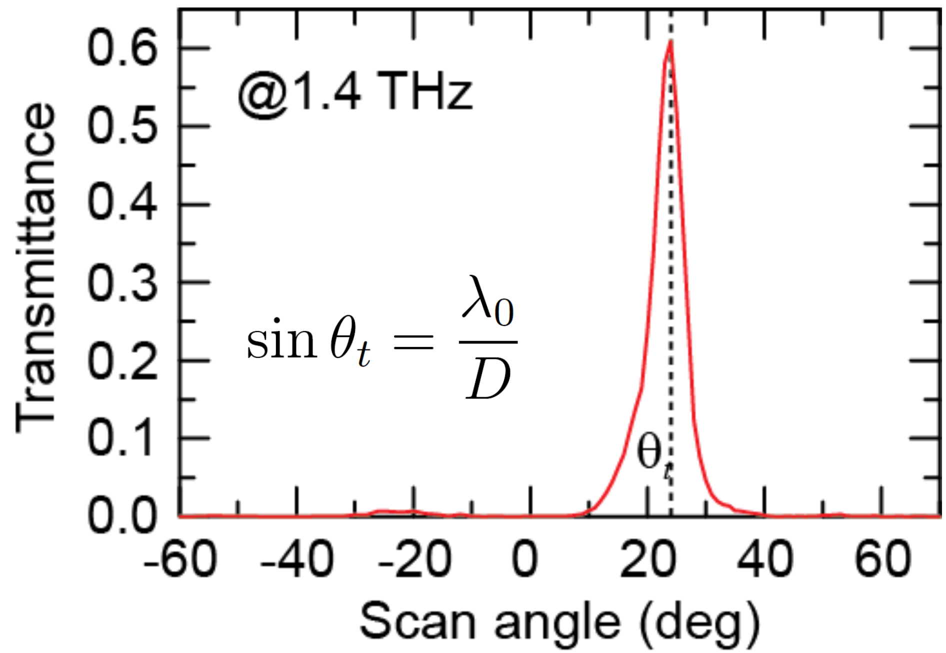
$$\sin\theta_t - \sin\theta_i = \frac{\lambda_0}{2\pi}\frac{\mathrm{d}\Phi}{\mathrm{d}x}$$

- ❑ Each individual element can be used in polarization converter
- ❑ Conversion efficiency is designed to be largely constant
- ❑ 8 elements form the unit cell, with a linear phase shift spanning a 2π range

Grady et al., *Science* **340**, 1304 (2013).

Near-Perfect Anomalous Refraction: Exp.

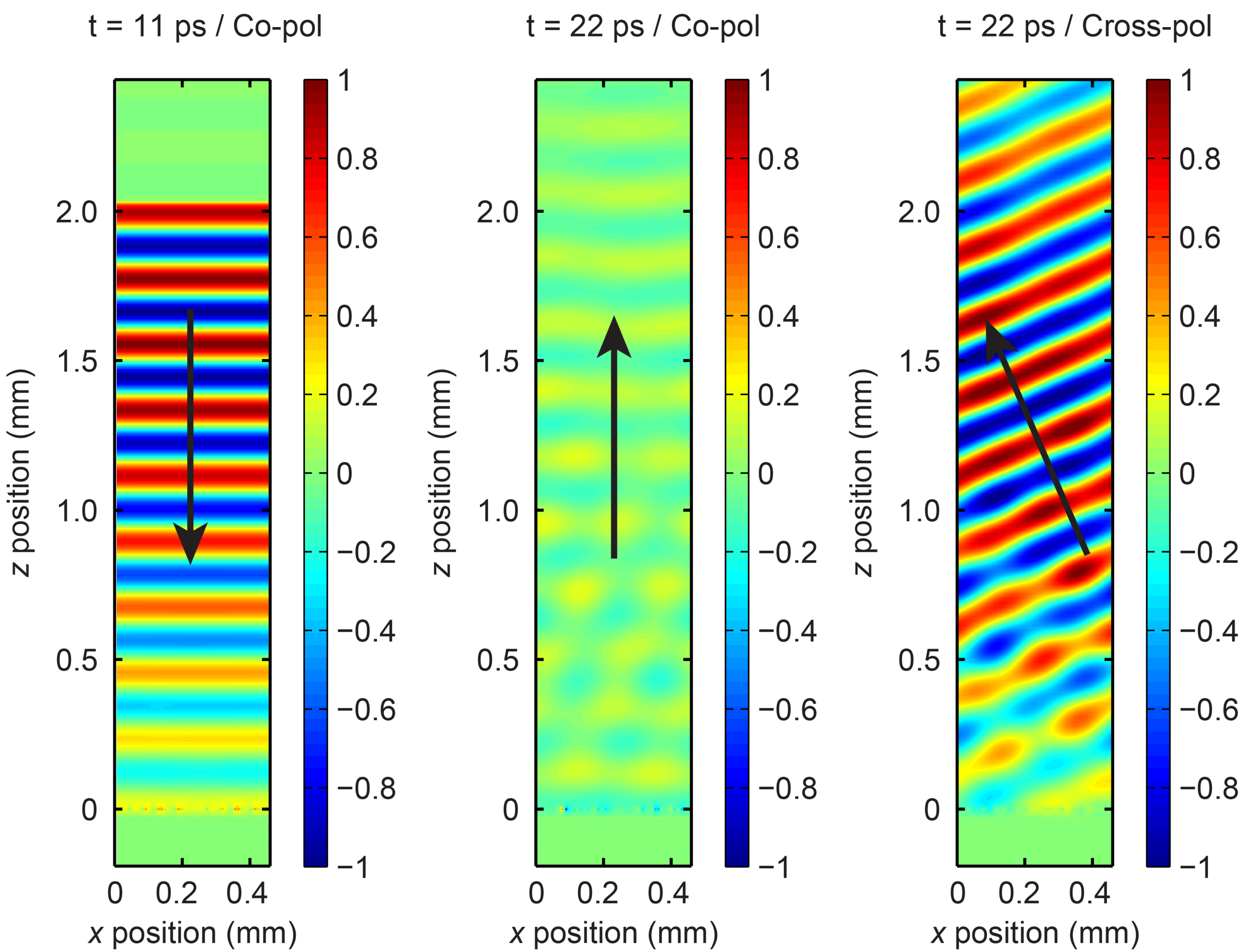




- ❑ At a specific frequency, the "refraction angle" is determined by periodicity
- ❑ At 1.4 THz, the anomalous refraction carries 60% of the incident power
- ❑ Measure the cross-polarized transmission *vs.* scanning angle
- ❑ Operate over a broad bandwidth

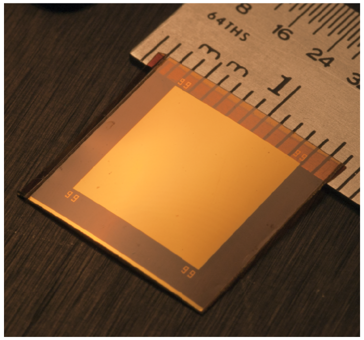
Grady et al., *Science* **340**, 1304 (2013).

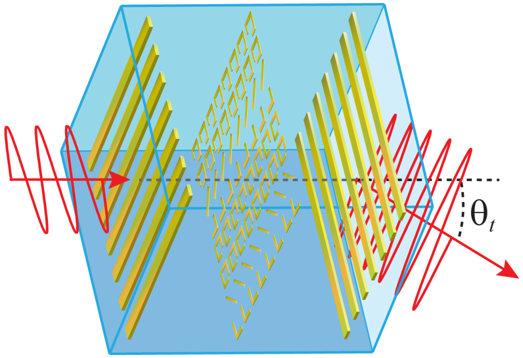
Near-Perfect Anomalous Reflection: Simulation

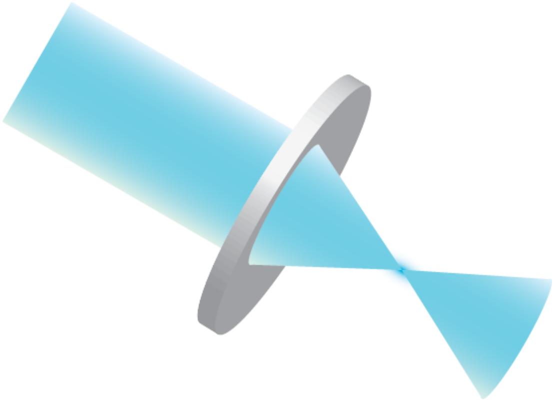


Grady et al., *Science* **340**, 1304 (2013).

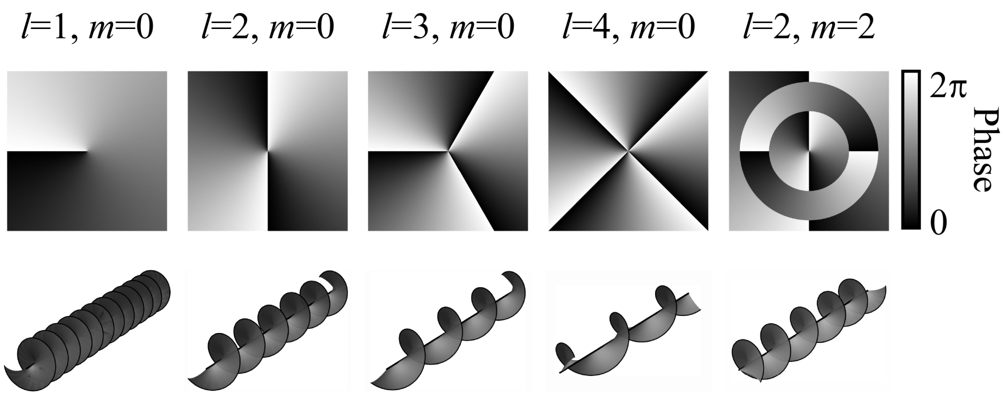
Flat Optics



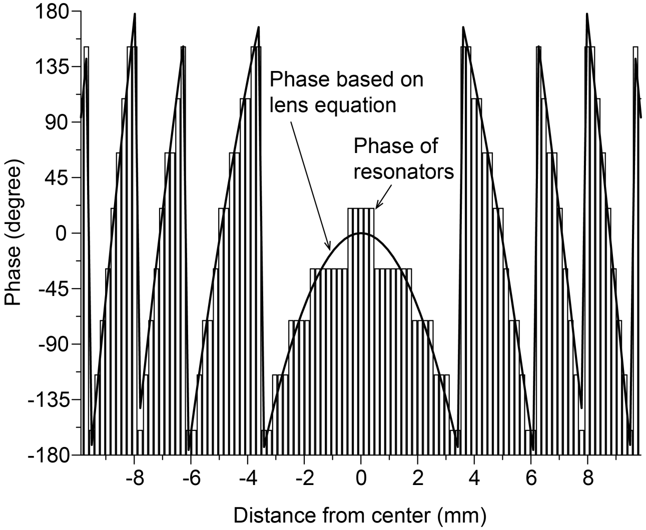




- Flat prism for beam steering

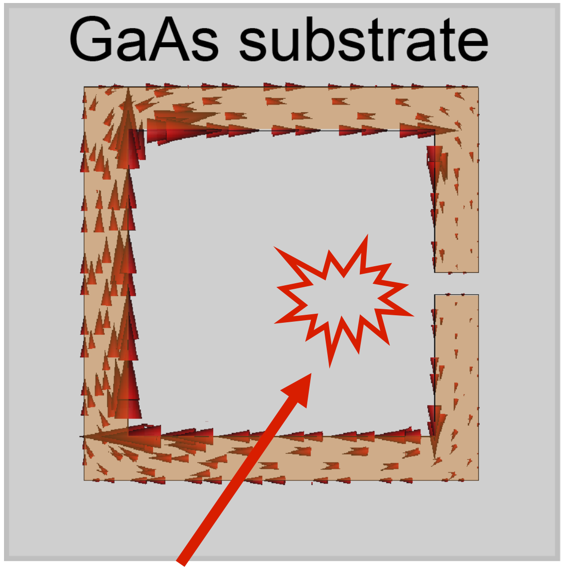


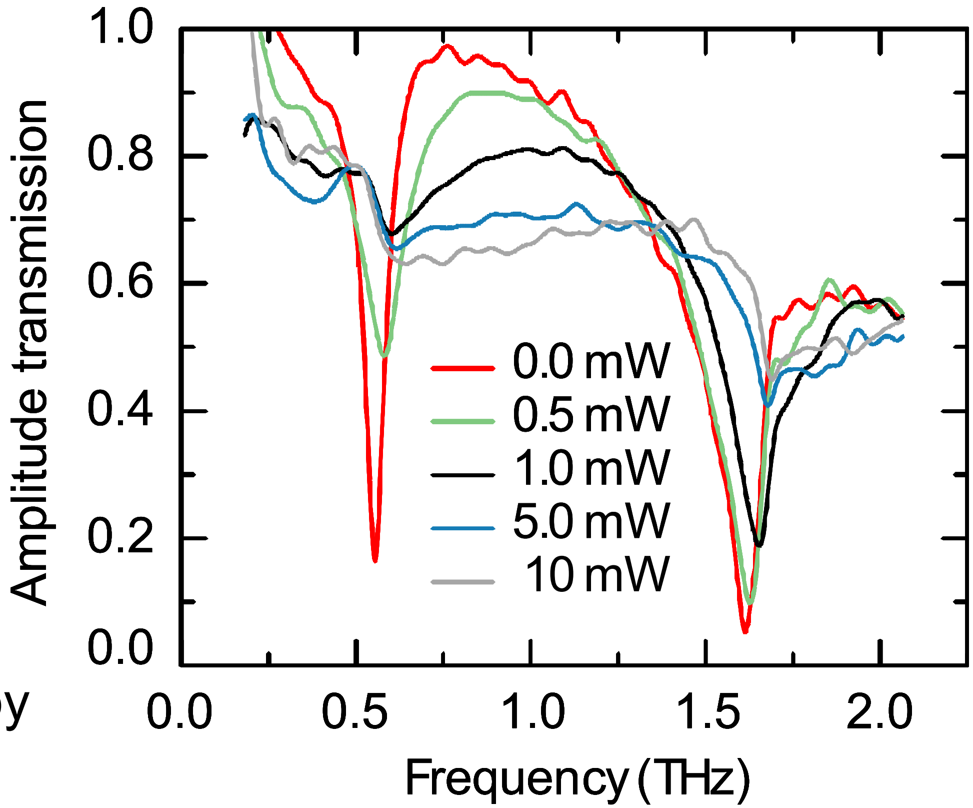
- Wave front shaping



- Flat lens for beam focusing

Optically Switchable Terahertz Metamaterials

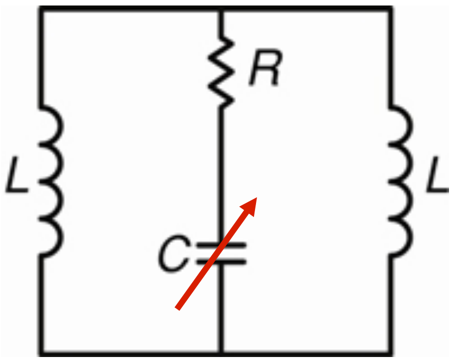


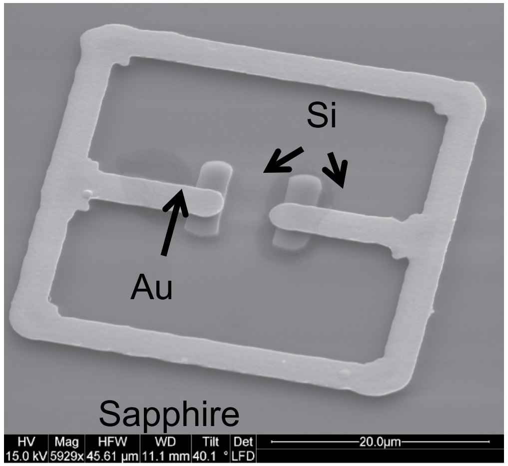


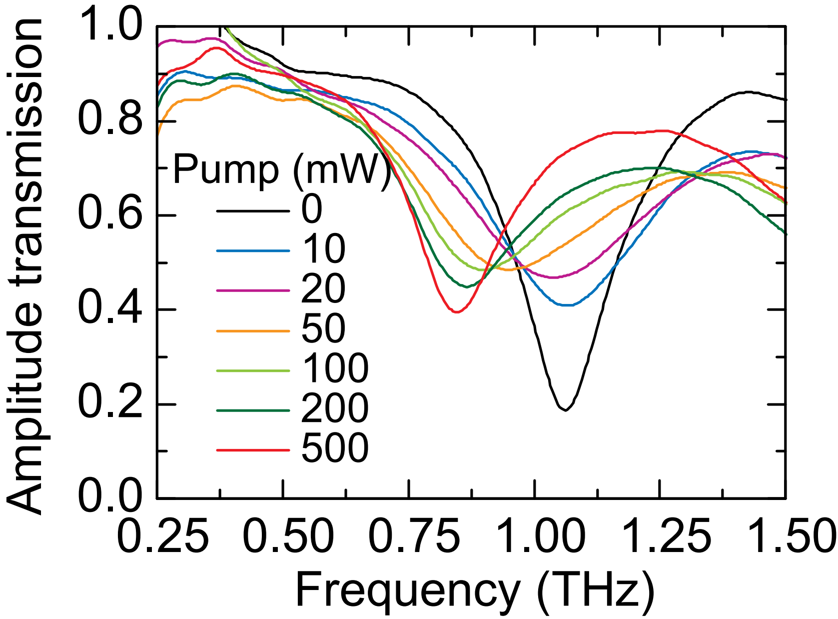
- Switching speed is only limited by carrier lifetime (~ns for GaAs)
- ~ps by reducing the carrier lifetime (GaAs:ErAs nano superlattice)

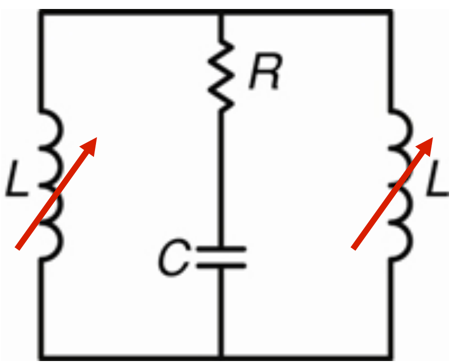
Padilla *et al.*, *Phys. Rev. Lett.* **96**, 107401 (2006).
Chen *et al.*, *Opt. Lett.* 32, 1620 (2007).

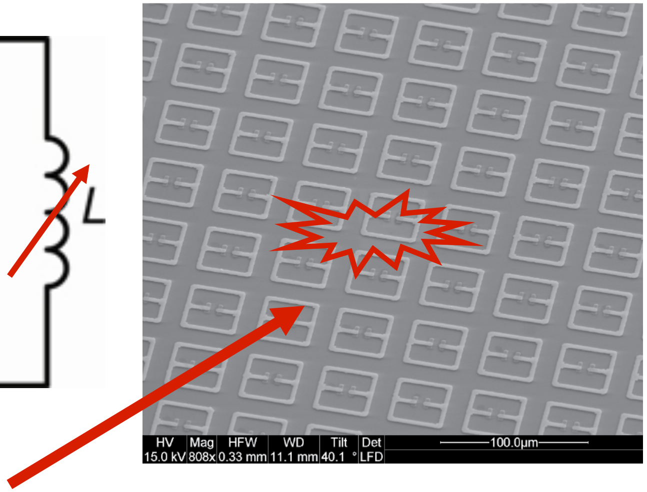
Optically Frequency Tunable Terahertz Metamaterials







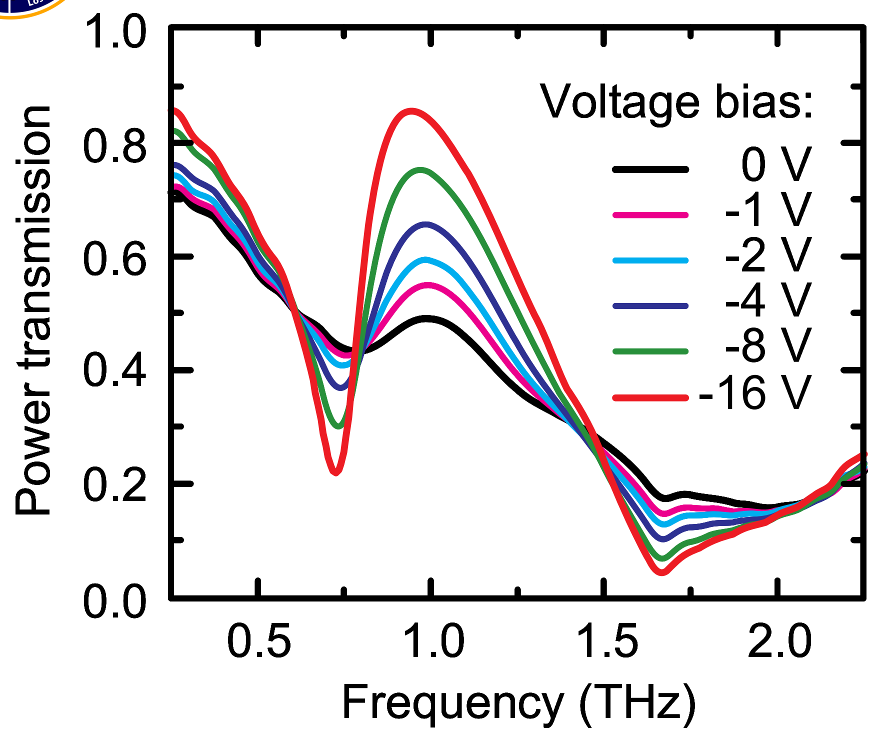


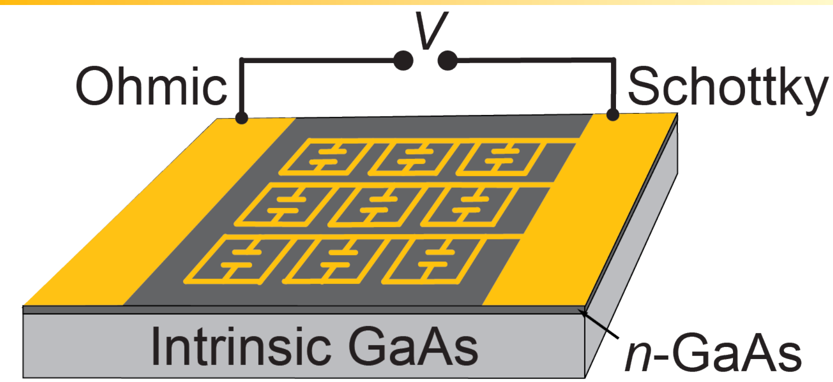


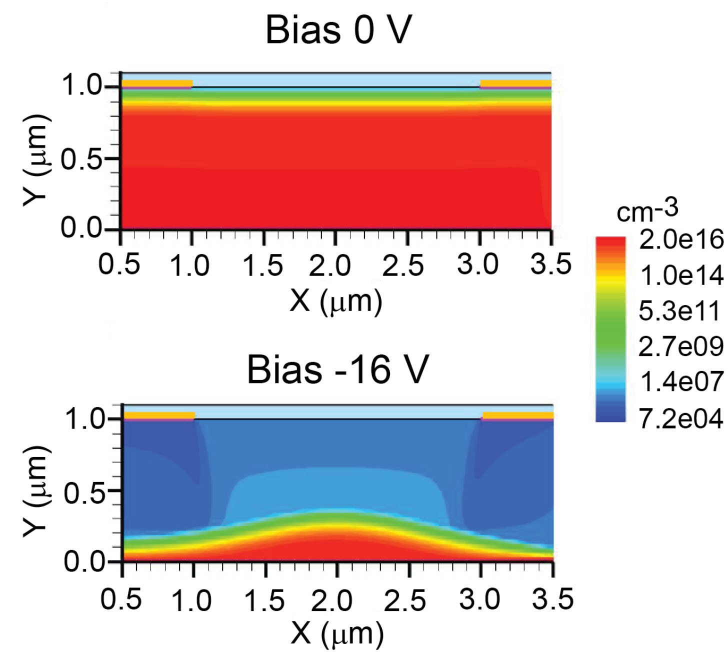
- ~20% frequency tuning range
- Could be red or blue shifting

Chen *et al.*, *Nature Photon.* **2**, 295 (2008).

Electrically Switchable Terahertz Metamaterials



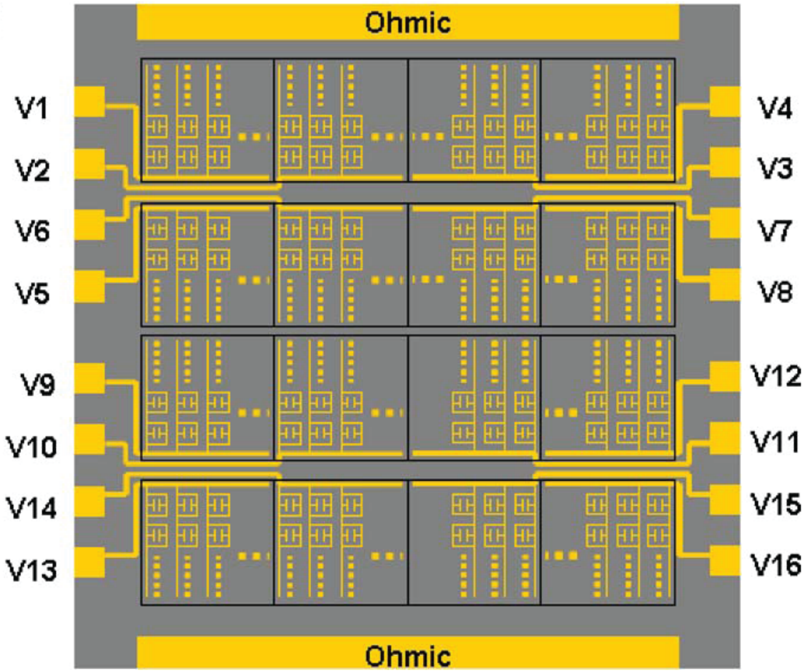


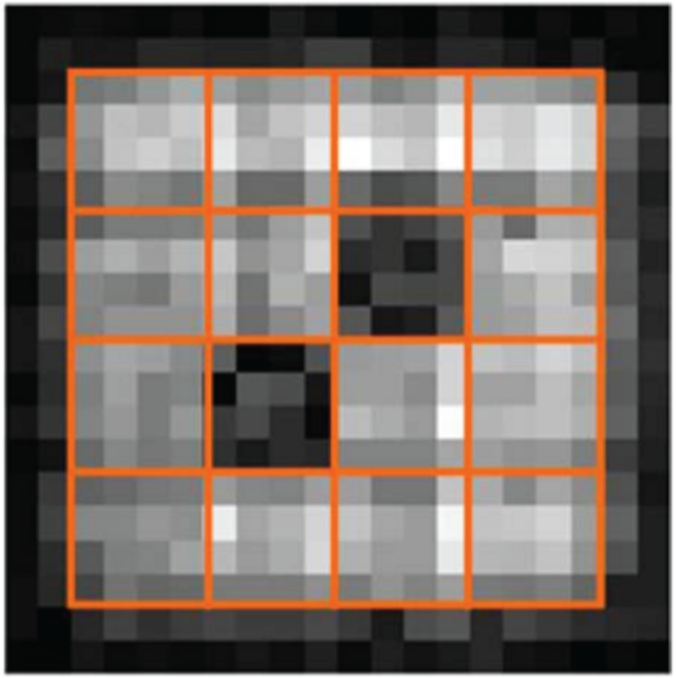


- Amplitude modulation depth 50%
- Phase modulation of $\Delta\varphi = \pi/6$
- Operate at room temperature

Chen *et al.*, *Nature* **444**, 597 (2006).
Chen *et al.*, *Nat. Photon.* **3**, 148 (2009).
Chen *et al.*, *Opt. Express* **16**, 7641 (2008).
Chen *et al.*, *APL* **93**, 091117 (2008).

Terahertz Spatial Light Modulator

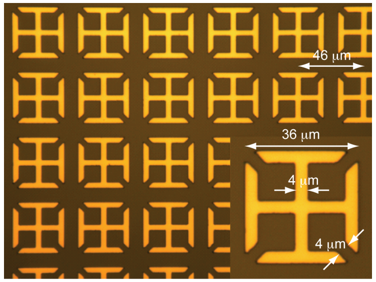




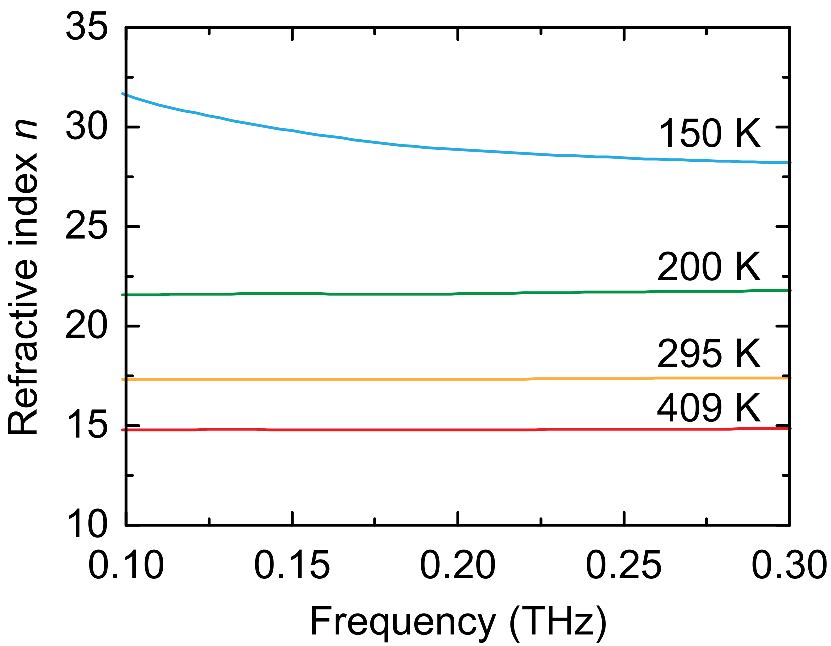
- Each pixel consisting of hundreds of SRRs
- Resonance can be independently switched at each pixel
- For high-speed terahertz imaging

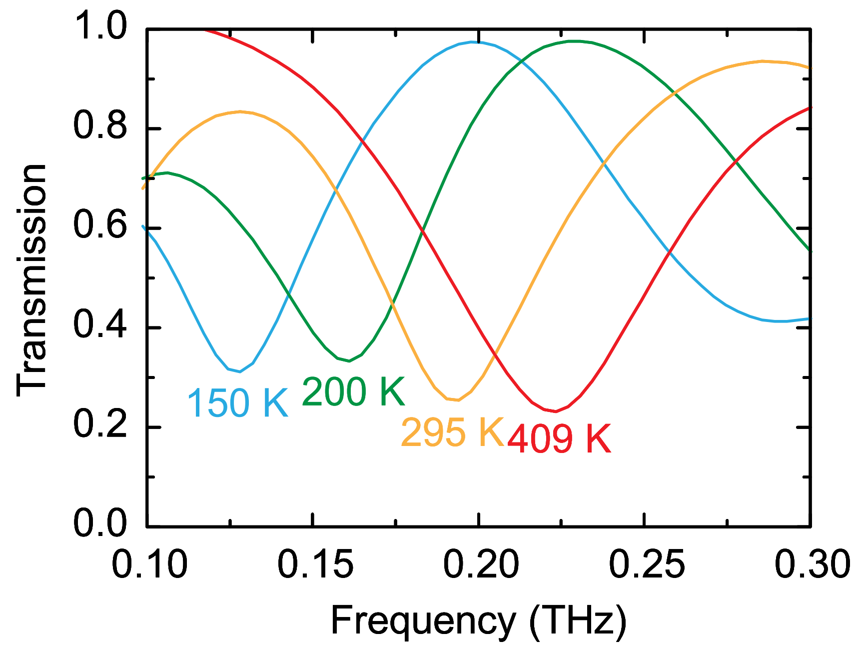
Chan *et al.*, *Appl. Phys. Lett.* **94**, 213511 (2009).

Thermally Tunable Metamaterials Using Ferroelectric Substrate (Strontium Titanate)



- Substrate refractive index (dielectric constant) decreases with decreasing temperature
- Resonance frequency red-shifts with decreasing temperature

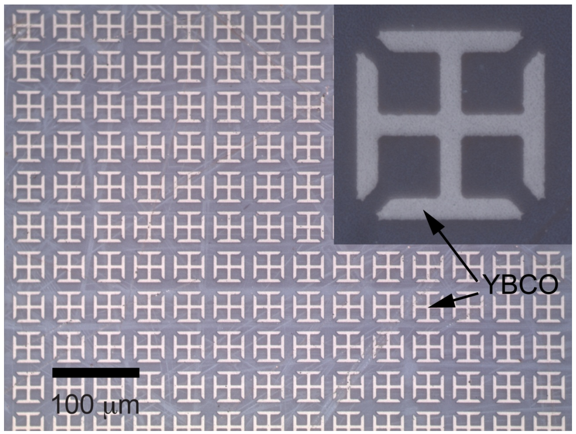


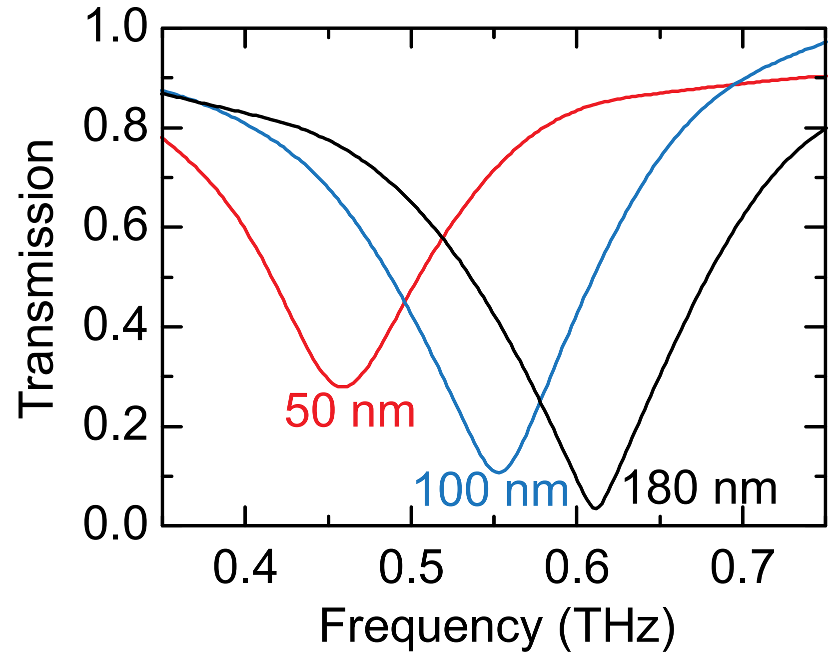


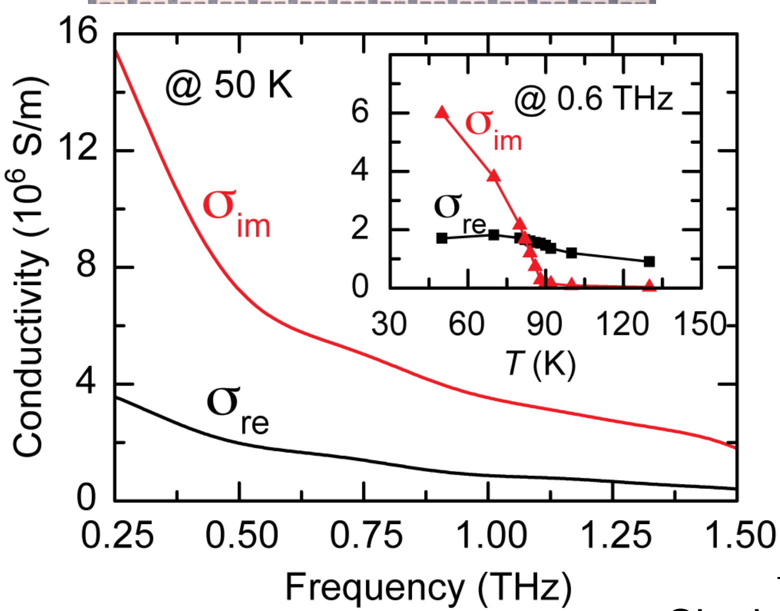
Singh *et al.*, *Opt. Lett.* **36**, 1230 (2011).

High-Temperature Superconducting (HTS) Metamaterials

Epitaxial YBCO film on LAO by Pulsed Laser Deposition with *Tc* ~ 90 K and thickness 180 nm





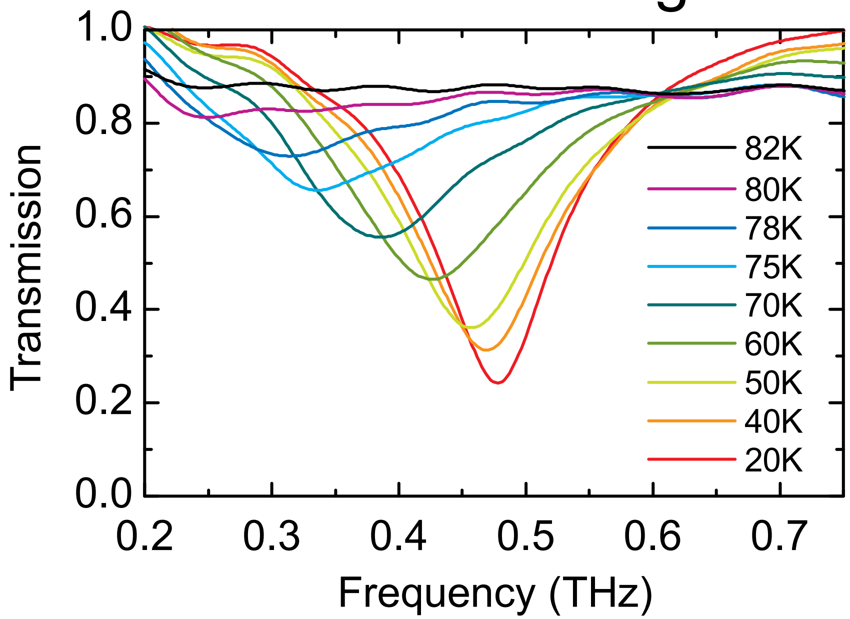


- Strong resonant response at low temperatures
- Resonance frequency strongly depend on the nano-scale thickness
- Need to take into account the kinetic inductance in YBCO metamaterials

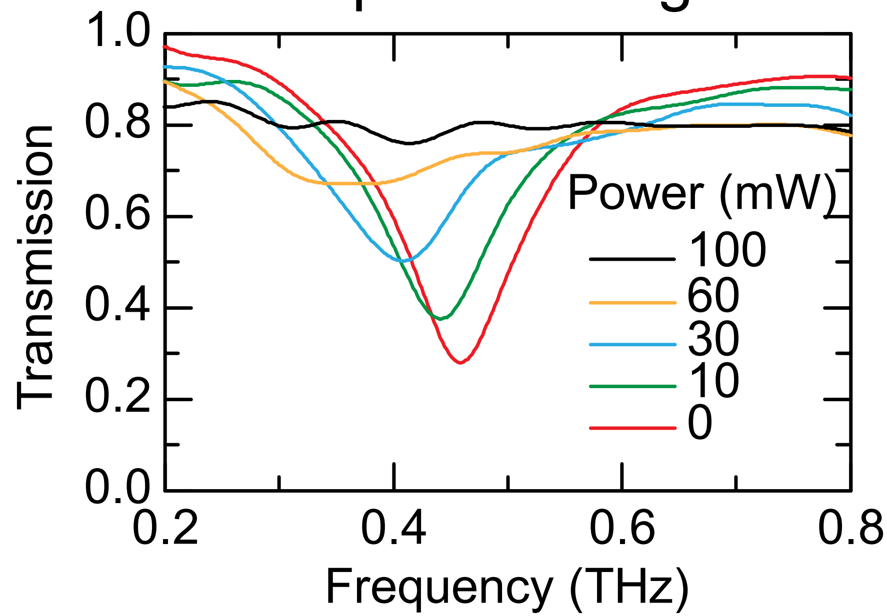
Singh *et al.*, *Nanophotonics* **1**, 117 (2012).

Thermal & Optical Resonance Tuning in HTS Metamaterials

Thermal tuning



Optical tuning



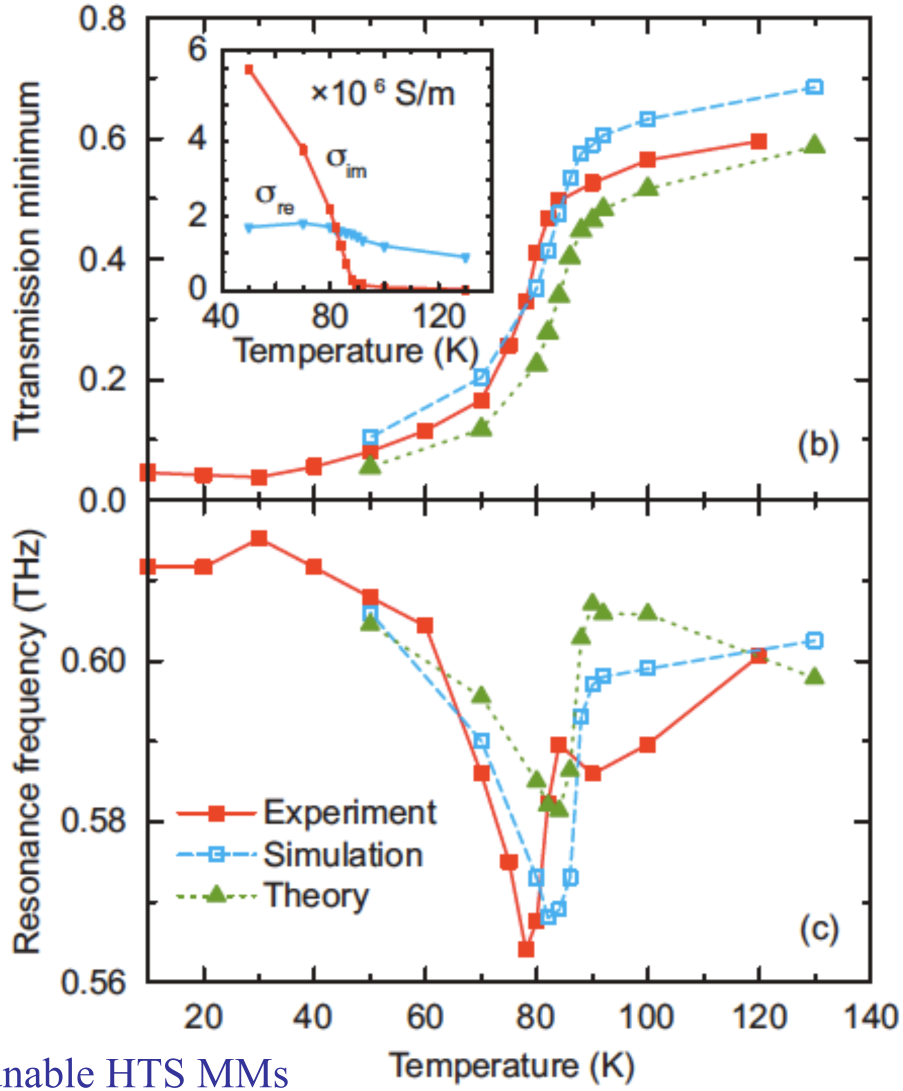
- 50 nm thick YBCO metamaterial
- Resonance strength and frequency are both tuned by temperature
- Imaginary conductivity plays a key role
- The resonance tuning is more significant in thinner YBCO metamaterials

Chen *et al.*, *PRL.* **105**, 247402 (2010).

Comparison: Experiment, Simulation, and Calculation

180 nm thick YBCO MM

- Measured, simulated and calculated values of transmission and resonance frequency in agreement.
- Use experimentally measured complex conductivity, plotted at 0.6 THz.
- Finite-element numerical simulations using Comsol Multiphysics
- Imaginary conductivity plays a key role through the kinetic inductance



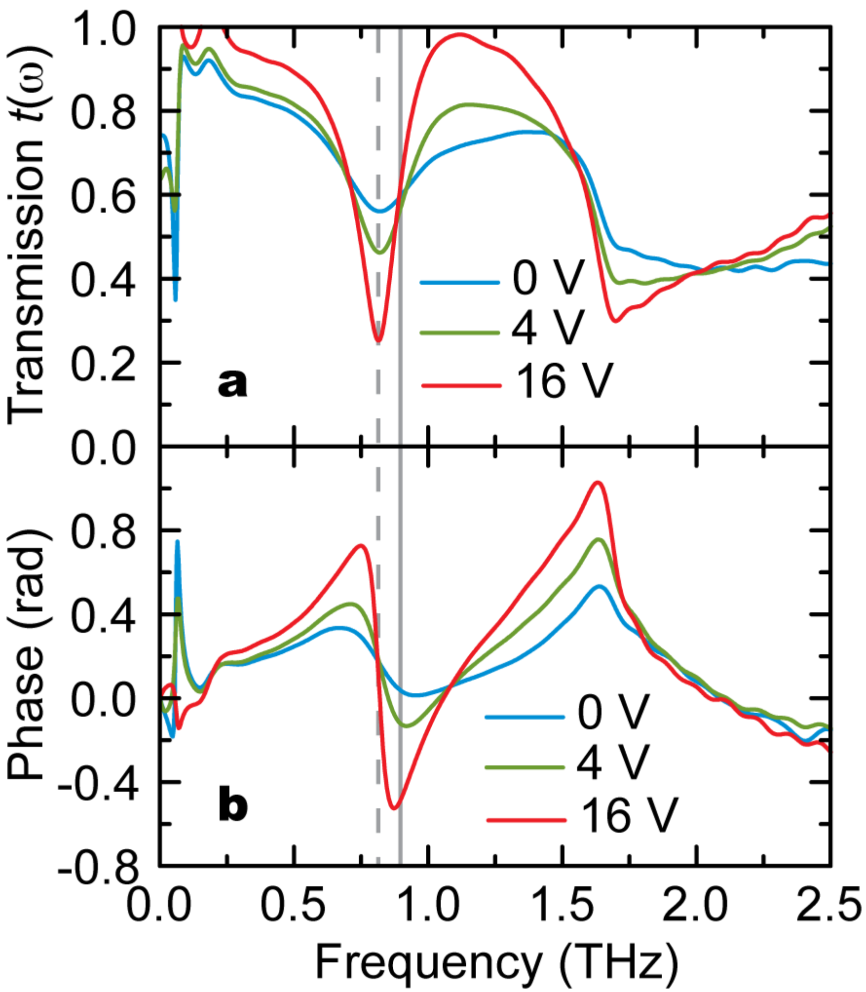
(Calculations for optically tunable HTS MMs are also in agreement with experiment.)

Metamaterials will play an increasingly important role in THz S&T

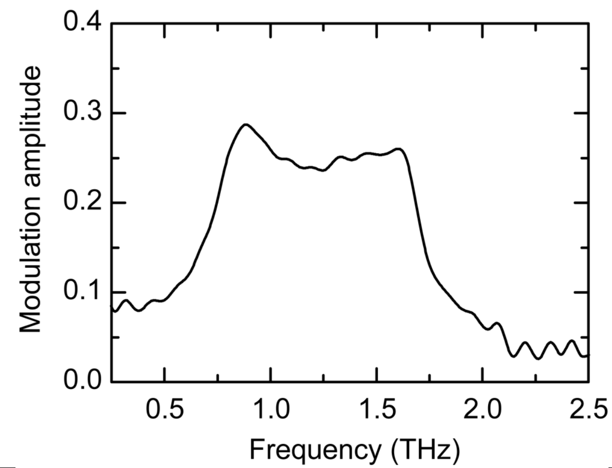
- Few-layered ultrathin planar metamaterials can accomplish many optical functionalities of bulk materials
  - Ultrathin metamaterial perfect absorbers
  - Ultrathin metamaterial antireflection coatings
  - Thin film like metamaterial linear polarization converters
  - Near perfect anomalous reflection/refraction: generalized Snell's law
- Electrically switchable THz metamaterials
  - High modulation (intensity and phase) depth
  - Integration into spatial modulator
  - Broadband modulation
- Optically switchable, frequency tunable THz metamaterials
  - Low optical fluence, high efficiency
  - Ultrafast switching
  - 20% frequency tunability
  - Temperature & optical tunability with complex oxide metamaterials

Back-up slides

Amplitude and Phase Modulation



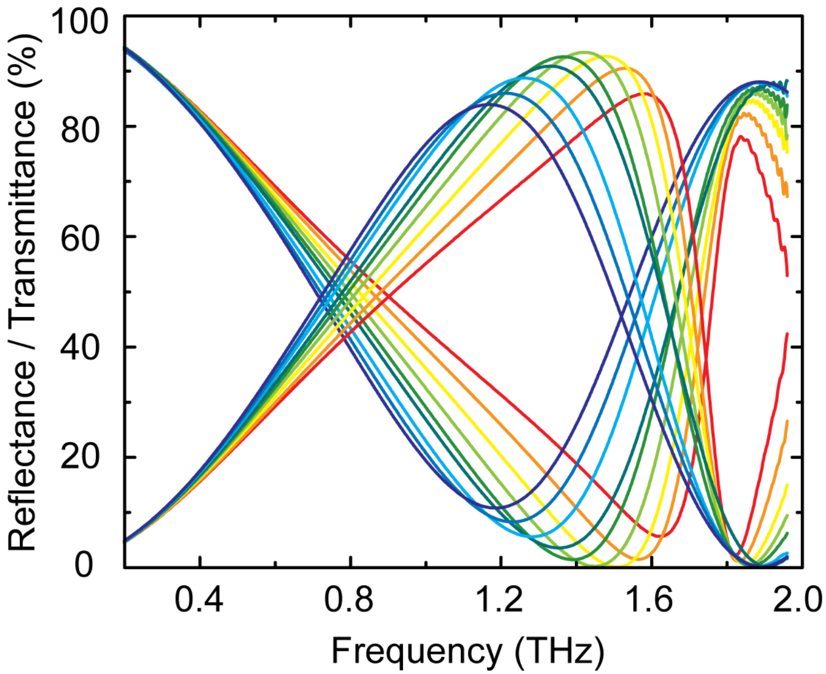
- Power modulation depth:
  $M = (T0\text{V} - T16\text{V}) / T0\text{V} = 80\%$, or amplitude modulation depth 55%
- Phase modulation $\Delta\varphi = \pi/6$
- Amplitude and phase modulations are correlated
- Both amplitude and phase modulations contribute to the modulation signal resulting in broadband modulation



$$|\Delta\tilde{t}(\omega)| = \left| t_{V1}(\omega) e^{i\phi_{V1}(\omega)} - t_{V2}(\omega) e^{i\phi_{V2}(\omega)} \right|$$

Chen *et al.*, *Nature Photon.* 3, 148 (2009).

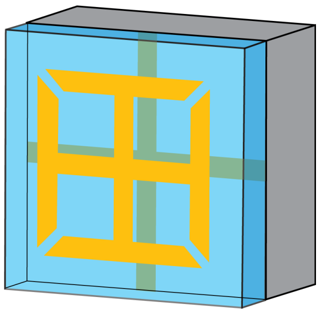
Numerical Simulations: Spacer Thickness



Simulation:

Substrate: ε_{GaAs} = 12.7

MM spacer: ε_{spacer} =1.5



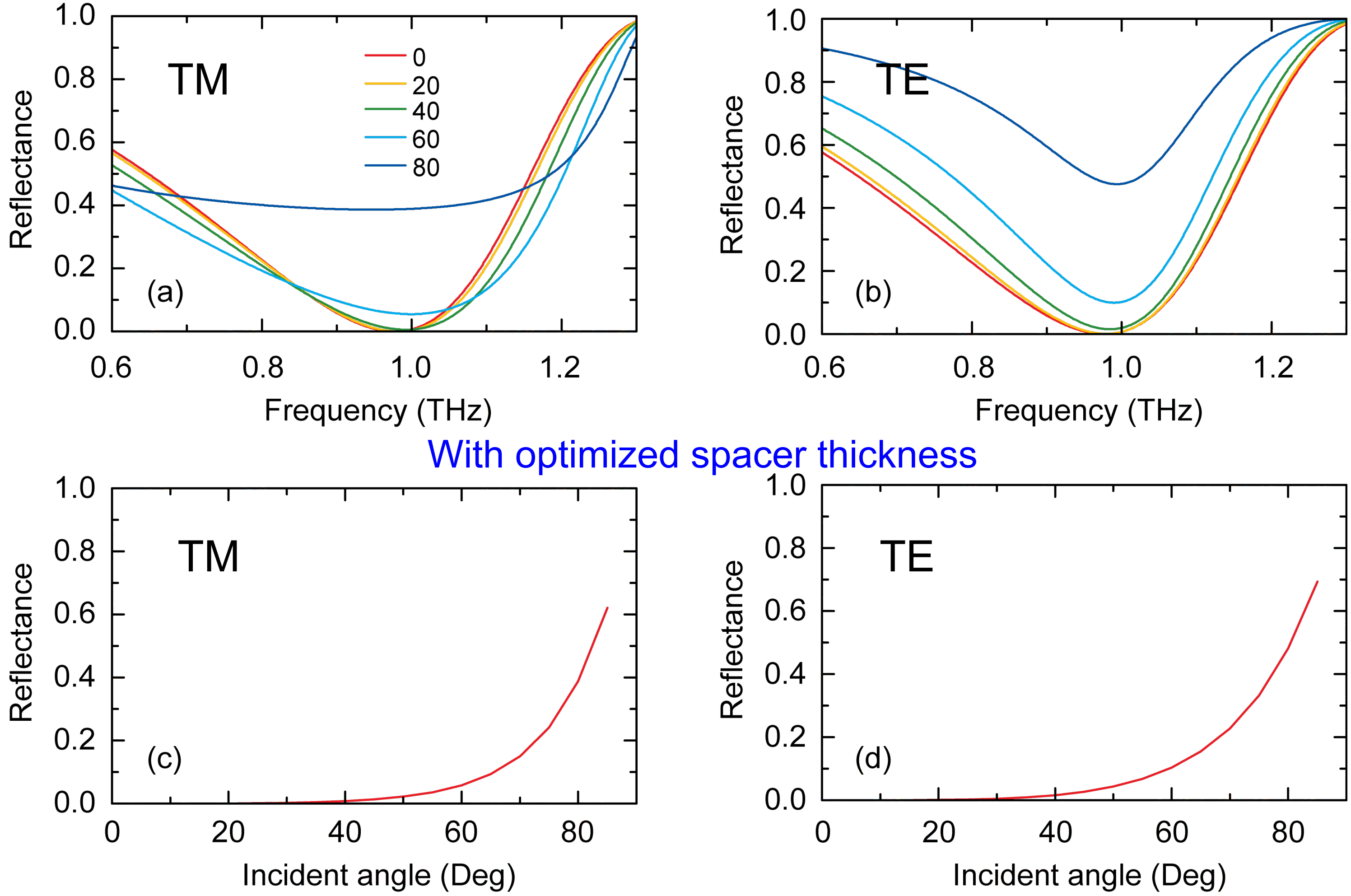
From red to blue:

Increasing the spacer thickness from 4 μm to 20 μm

- With any dielectric constant of the spacer material, there is always a thickness achieving excellent antireflection, even the spacer dielectric constant is larger than the substrate
- The losses in metal and the spacer material mainly affect the transmittance, but has little effect on the reflectance

Chen *et al.*, *Phys. Rev. Lett.* **105**, 073901 (2010).

Numerical Simulations: Angular Dependence



Chen *et al.*, *THz Sci. & Technol.* **3**, 66 (2010).

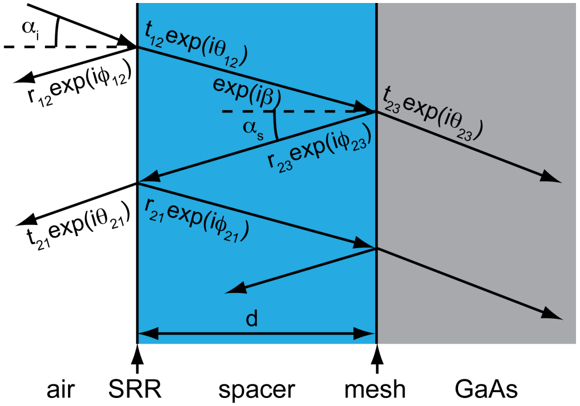
Antireflection Mechanism: Modeling Results

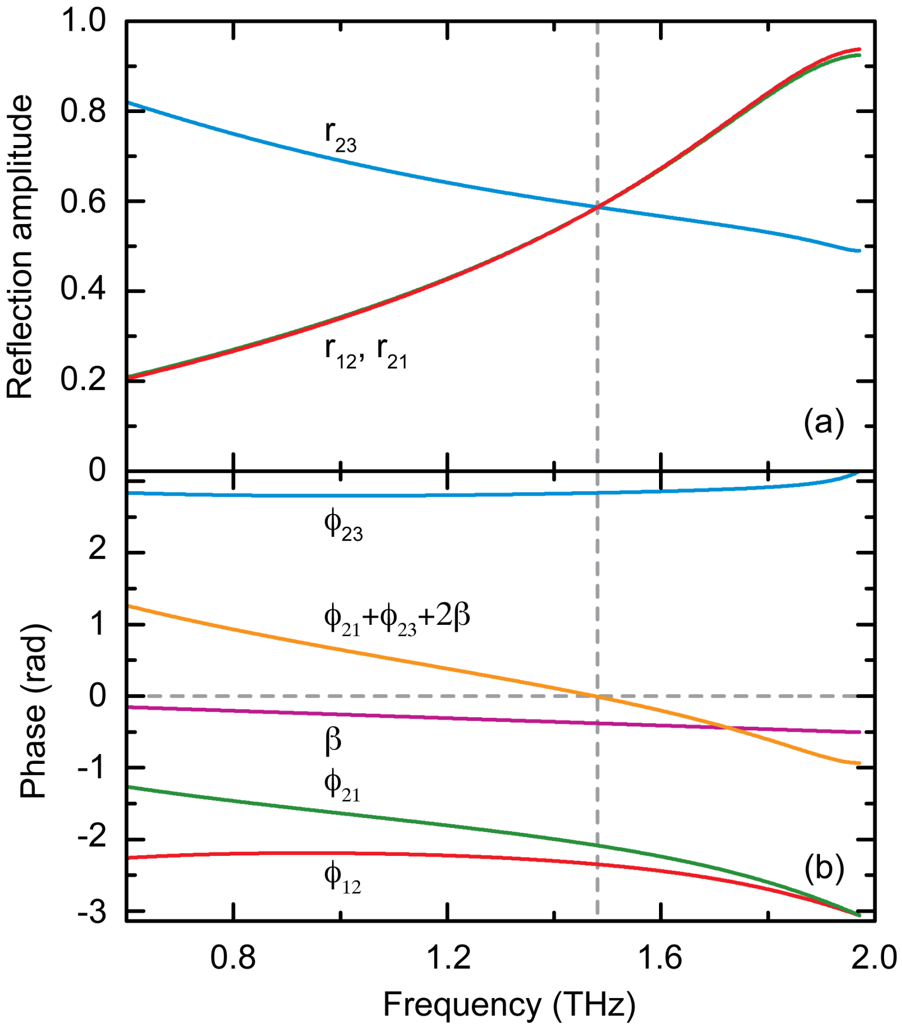
- Antireflection requirements:

$$r_{12} = r_{21} = r_{23},$$

$$\phi_{21} + \phi_{23} + 2\beta = 2m\pi$$

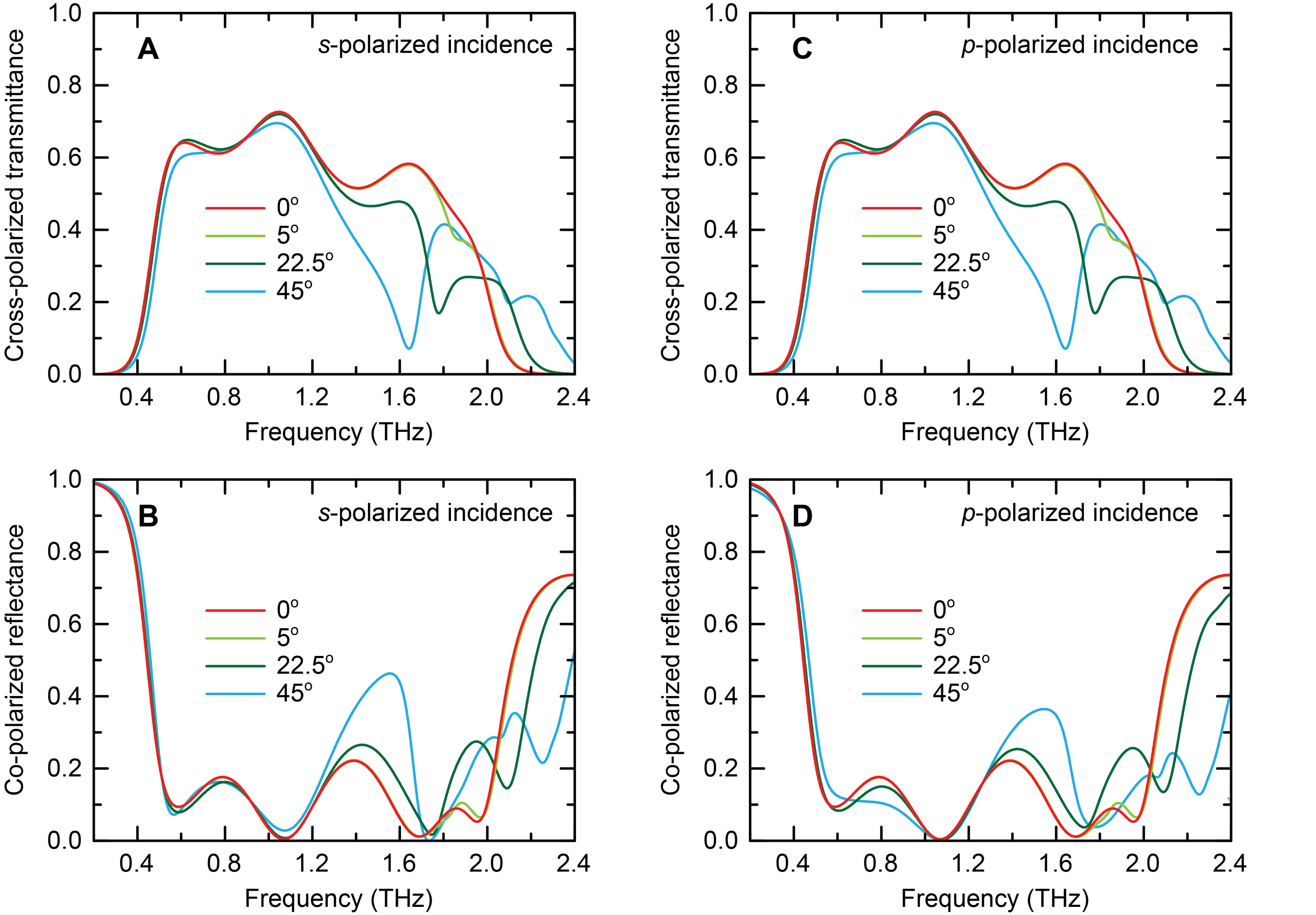
- Varying β (spacer thickness) reproduces the thickness dependent reflection and transmission





Chen *et al.*, *Phys. Rev. Lett.* **105**, 073901 (2010).

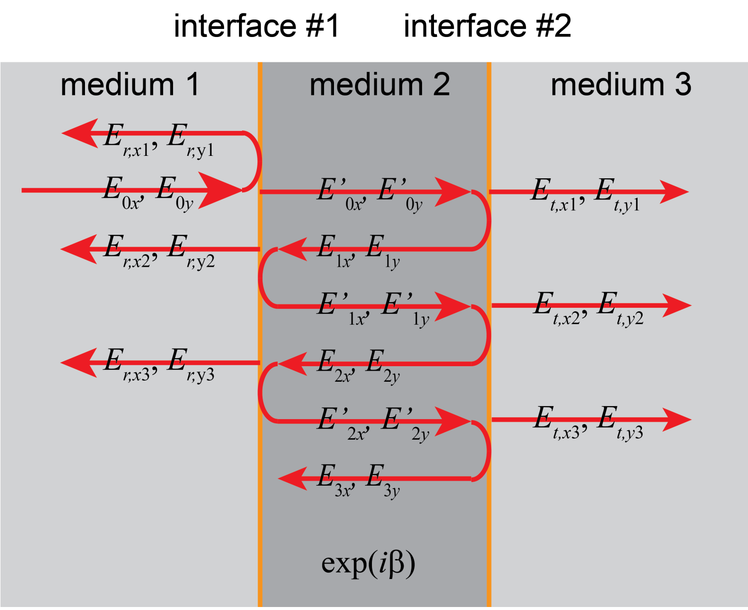
Polarization and Incident Angle Dependence

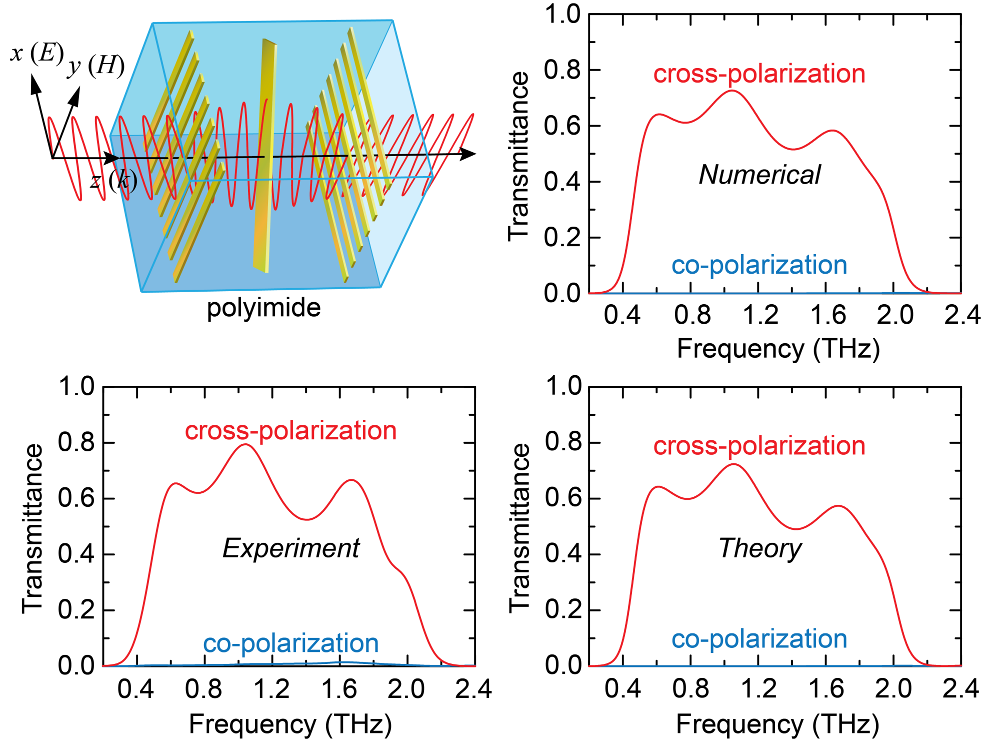


Grady et al., *Science* **340**, 1304 (2013).

Modeling Metamaterial Polarization Conversion

- Reflection and transmission coefficients from numerical simulations
- Superposition for the overall reflection and transmission





Grady et al., *Science* **340**, 1304 (2013).

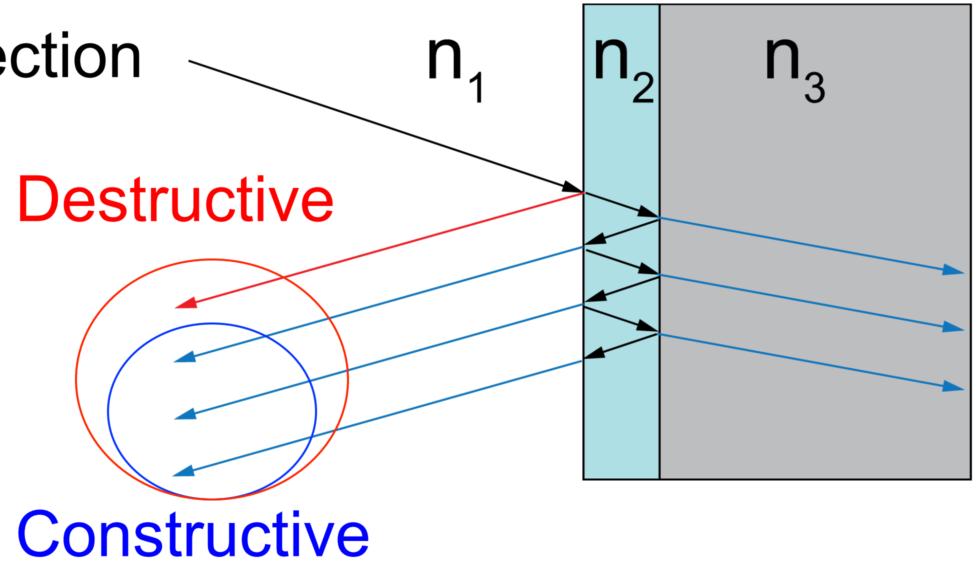
Antireflection Coatings

- Quarter-wave antireflection

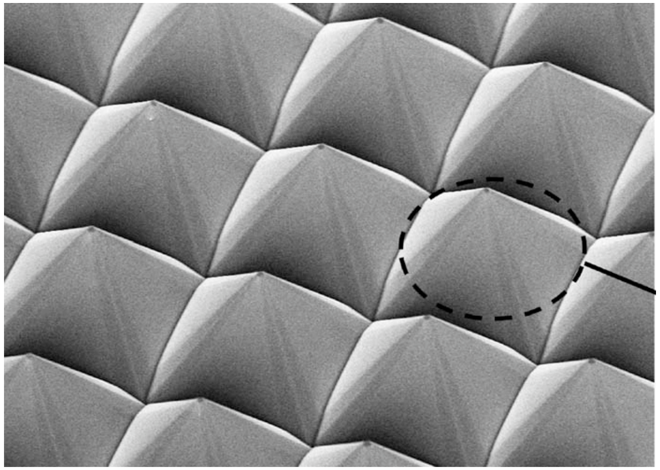
$$n_2 = \sqrt{n_1 n_3}$$

$$d = \lambda / 4$$

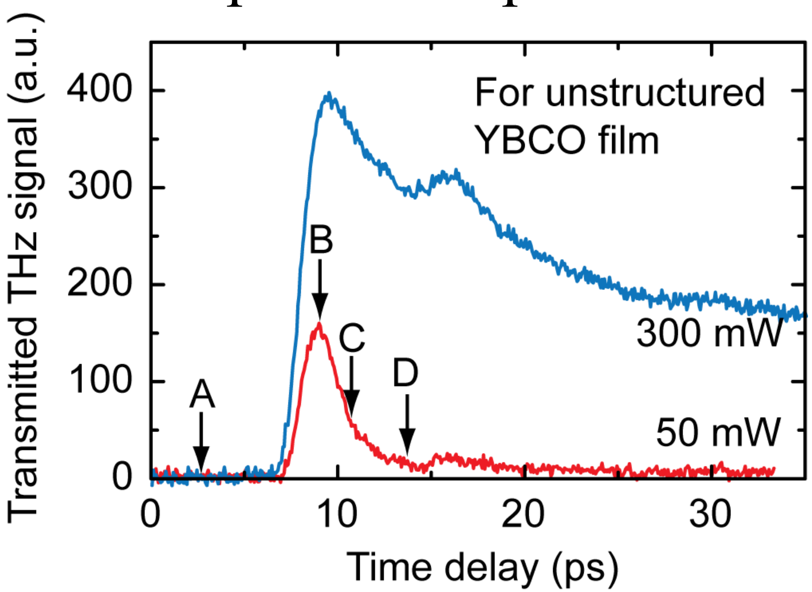
  - ✓ Index matching
  - ✓ Thick coating

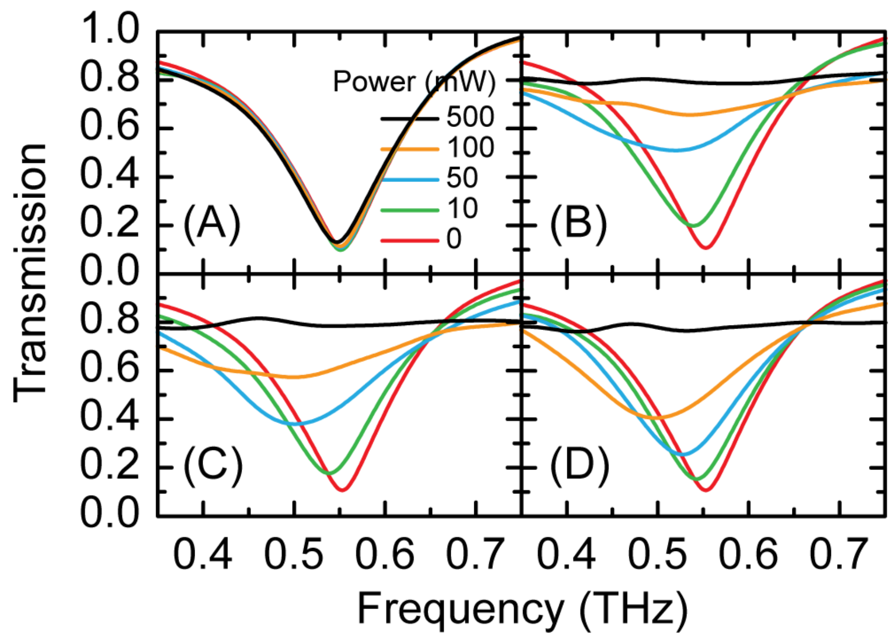


- Antireflection using surface relief structures
  - ✓ Specific for certain materials
  - ✓ Surface is no longer smooth for further integration



Ultrafast Dynamics

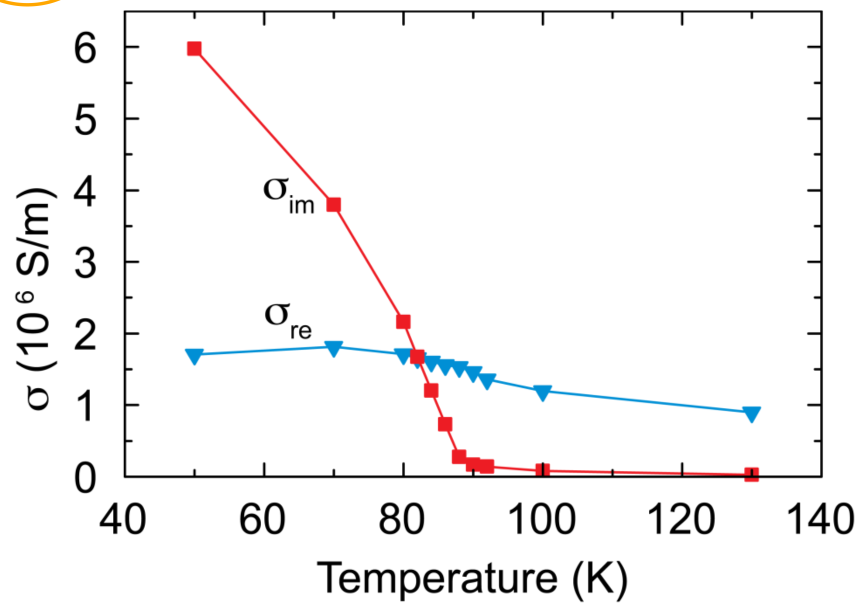


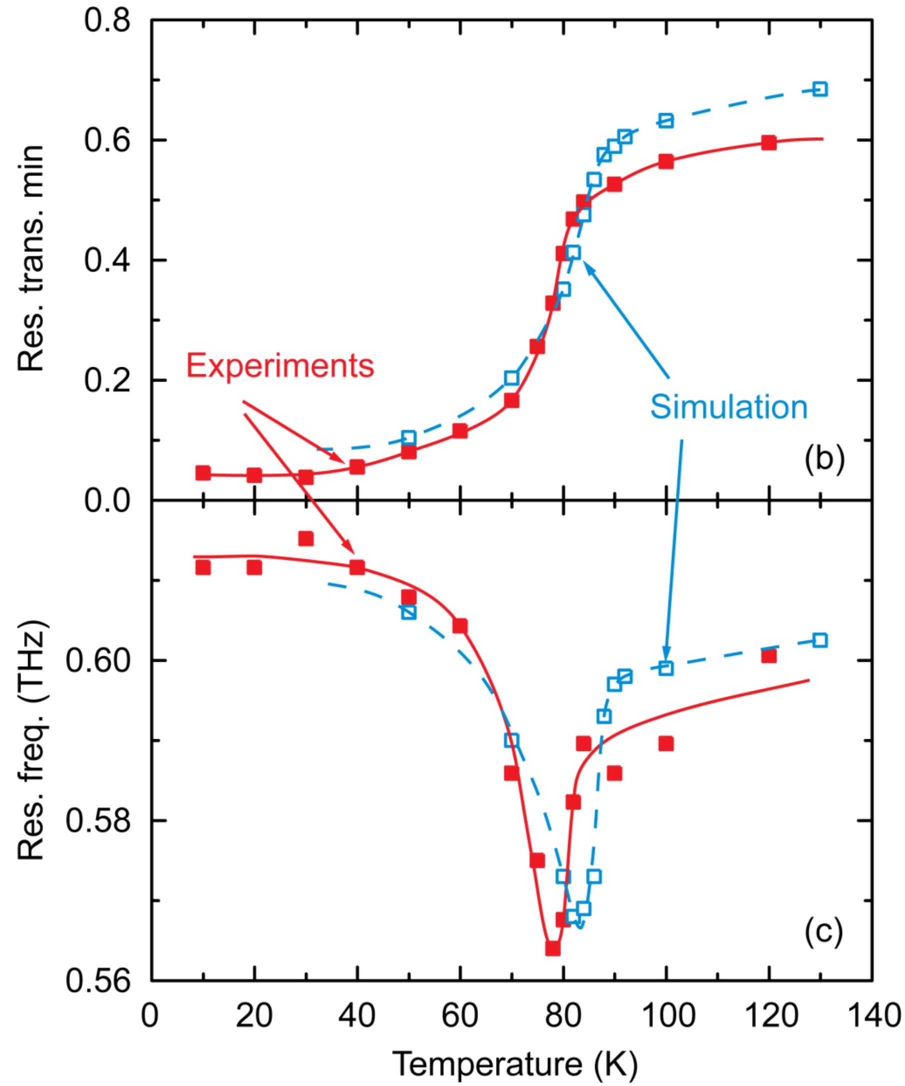


- Relaxation (recombination) time is a few ps
- Increasing the pump power results in a long relaxation tail due to thermal effects

Singh *et al.*, *Nanophotonics,* (2012), in press

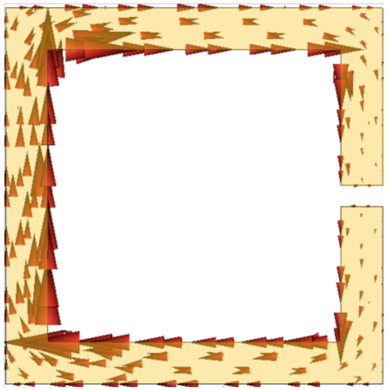
Thermally Tunable Resonance: Experiment and Simulation

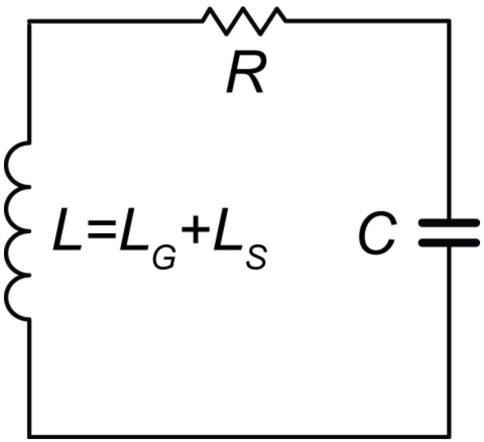




- Experimentally measured the complex conductivity, plotted at 0.6 THz
- Finite-element numerical simulations using Comsol Multiphysics

Resonance in Split Ring Resonators





- The resonance frequency is given by:

$$\omega^2 = \frac{1}{LC} - \frac{R^2}{4L^2}$$

- The capacitance C: determined by the geometry and dimensions of the split gap, and assume no change
- The inductance L:
  - ✓ Loop L_G
  - ✓ Additional (kinetic) inductance L_S from SRR superconducting strips
- L_S becomes important when the film thickness is comparable or smaller than the skin depth

SRR Resistance and Inductance

- Surface impedance:

$$\tilde{Z}_S = R_S - iX_S = Z_0 \frac{n_3 + i\tilde{n}_2 \cot\tilde{\beta}}{\tilde{n}_2^2 - n_3^2}$$

$$\tilde{n}_2 = \sqrt{i\sigma/\varepsilon_0\omega} \qquad \tilde{\beta} = \tilde{n}_2 d\omega/c_0$$

- When $|\tilde{n}_2| \gg n_3$, it can be simplified as:

$$Z_S = i\frac{Z_0}{\tilde{n}_2}\cot\tilde{\beta}$$

- By considering the non-uniform currents, the surface resistance of the *SRR array* is given by:

$$R = \frac{A}{w} R_S$$

  - *A* is the loop circumference
  - *w* is the SRR linewidth

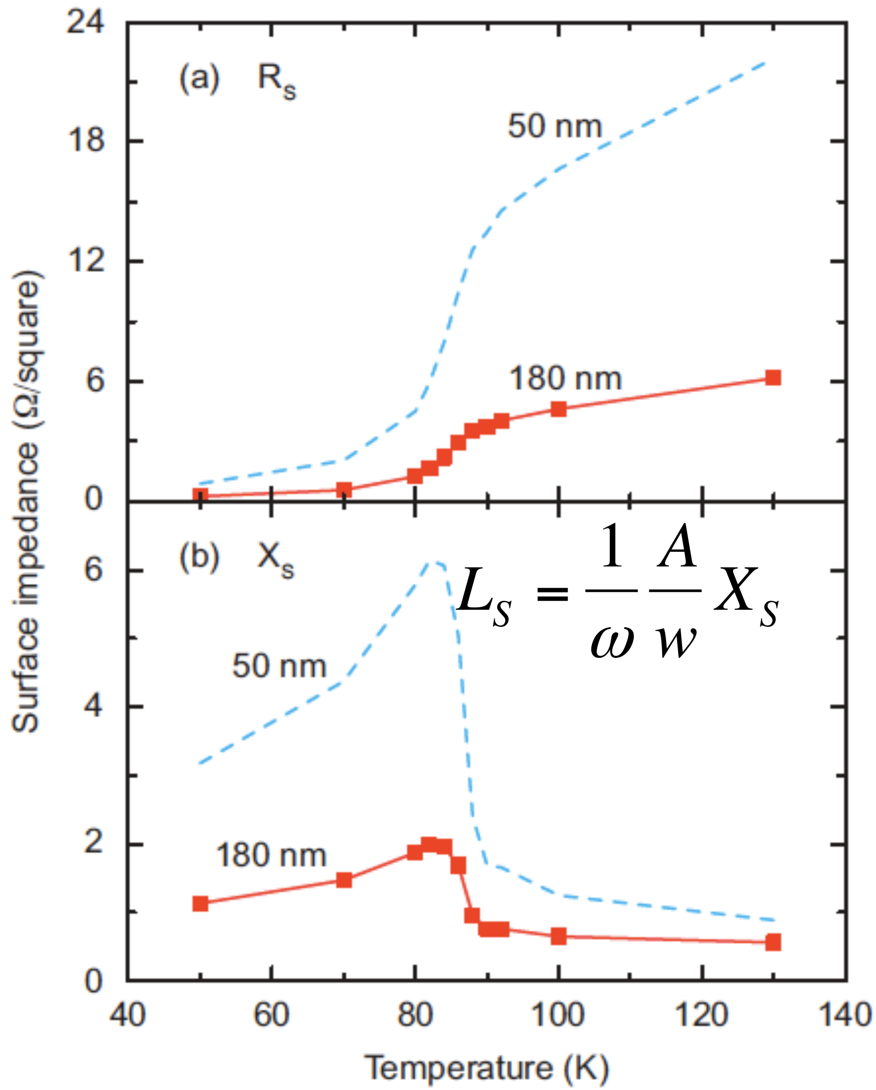
- Additional kinetic inductance:

$$L_S = \frac{1}{\omega}\frac{A}{w} X_S$$

Thickness Dependent Surface Impedance

When reducing the HTS film thickness:

- Increasing surface resistance R_S: high damping for thinner YBCO metamaterials
- Increasing kinetic inductance L_S: lower resonance frequency for thinner YBCO metamaterials
- The turning point in L_S results in the resonance frequency back shift.



$$L_S = \frac{1}{\omega}\frac{A}{w}X_S$$